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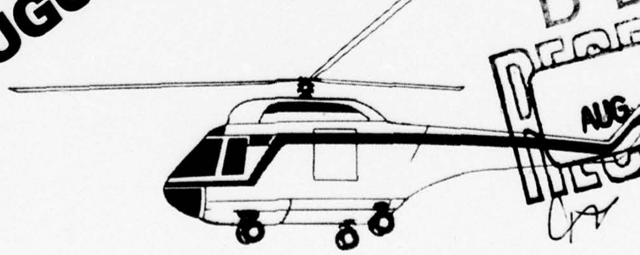
PROGRESS REPORT

SYSTEMS RESEARCH AND DEVELOPMENT SERVICE

PROGRESS REPORT
AUGUST 8-9, 1978



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16. Abstract

The 37 technical papers contained in this document provide the details of selected topics of major research and development efforts being undertaken by the Systems Research and Development Service of the Federal Aviation Administration. Emphasis is placed on recent achievements and of expected results in the near future.

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A REPORT OF PROGRESS

It's my pleasure to present to you this compilation of technical reports authored by various staff members of the Systems Research and Development Service.

This document together with our 2 days of presentations hopefully gives you an in-depth understanding of the major research and development programs now underway.

Our purpose in serving the aviation public is to formulate and conduct a program which is both responsive to problems experienced in today's operation and responsive to our perception of future conditions.

Your judgment of our effectiveness toward this purpose will be welcome.

DAVID J. SHEFTEL
Director, Systems Research and Development Service, ARD-1

This report contains 37 papers prepared by various divisions of the

SYSTEMS RESEARCH AND DEVELOPMENT SERVICE. Reports are included

PROGRESS REPORT

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from the

SYSTEMS RESEARCH AND DEVELOPMENT SERVICE

PROGRESS REPORT

CONTENTS

EN ROUTE MINIMUM SAFE ALTITUDE WARNING FUNCTION (E-MSAW) INTEGRATED WITH THE CURRENT NAS AUTOMATION SYSTEM

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BIOGRAPHY

James P. Dugan is a computer system analyst within the En Route Branch of the ATC Systems Division SRDS. Before joining the FAA in 1959, he spent 12 years at the Ballistic Research Laboratory at Abredeen Proving Grounds, Maryland, where he worked on some of the early digital computers. From 1959 to 1966, he was at the FAA's National Aviation Facilities Experimental Center (NAFEC), in New Jersey, and 1966 moved to the Data Processing Branch of the ATC Development Division SRDS.

ABSTRACT

The En Route Minimum Safe Altitude Warning (E-MSAW) function will provide in the NAS En Route Computer System an automated aid to the controller, alerting him to situations when a tracked aircraft is below or will soon be below a predetermined minimum safe altitude. The current E-MSAW development effort evolved from a Terrain Avoidance project developed by SRDS for feasibility testing at the Albuquerque ARTCC in 1976.

This paper is limited to a discussion of aircraft in the en route overflight and transitioning environment, i.e. it does not include non-approach control airspace. The paper covers the development products and activities as well as the technical approach to be followed. A demonstration will be completed at the National Aviation Facility Experimental Center (NAFEC) at Atlantic City, New Jersey, prior to undertaking field evaluations at Memphis and Albuquerque Centers. The program will culminate in national implementation of the E-MSAW function in 1979.

ACRONYMS

ACES	Adaptation Control Environment System
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
E-MSAW	En Route Minimum Safe Altitude Warning
EWA	E-MSAW Warning Altitude
HGFA	High Gross Filter Altitude
MEA	Minimum En Route Altitude
MGFA	Middle Gross Filter Altitude
MTA	Minimum Track Altitude
MVA	Minimum Vectoring Altitude
MWA	Maximum Warning Altitude
NAS	National Airspace System
NAS 3d2.8	Version 8 of the National Computer Program
RSB	Radar Sort Box
TAV-05	Terrain Avoidance, fifth version
VFR	Visual Flight Rules
UDS	Universal Data Set
VLAT	Vector Looklahead Time

BACKGROUND

This paper contains a discussion of the objectives and design of an En Route automation enhancement called En Route - Minimum Safe Altitude Warning (E-MSAW).

The current E-MSAW development effort has evolved from a Terrain Avoidance (TAV-05) project developed by SRDS and tested at the Albuquerque ARTCC in 1976. TAV-05 was basically a feasibility study and provided the background and foundation for operational requirements upon which the current effort is based.

Data obtained from field tests of TAV-05 at the Albuquerque ARTCC were analyzed to assess the feasibility of the experimental design. It was evident that major areas required more precise definition. These major areas included definition of safe altitude airspace, the determination of lookahead time that can be supported by the NAS horizontal and vertical trackers, minimizing the false alarm rate, and provision for arrivals/departures from non-approach control airports.

In TAV-05 the design of hazardous airspace was based solely upon definition of terrain elevation and, in special cases upon definition of natural and man-made obstacles. General terrain could be modelled only to a

precision afforded by 16x16 N.M. boxes, each with an associated minimum safe altitude. Individual obstacles were modelled by right circular cylinders.

A two-minute lookahead (maximum warning) time produced an excessive number of false alerts for departure and arrival flights in the vicinity of Terminal Area airspace and nonapproach-control airports, so that sterilization of this airspace was necessary. Further reduction in coverage by the TAV function was required to eliminate false alarms in the vicinity of turns at navigation fixes, resulting in the definition of special turn areas for the suppression of alerts. The complexity of the functional design placed undue burden on the adaptation of airspace. The factors involved in having a properly performing E-MSAW program were more complex than initially envisioned. The effort to shortcut a normal developmental cycle was not successful and Air Traffic Services requested that Research and Development inititate the current development plan (Reference 1).

To ease implementation of an E-MSAW function into the present ATC system a two-phase development program has been defined. Phase I E-MSAW function would provide service for aircraft in the en route overflight and transitioning environment and Phase II would include service to aircraft operating in the non-approach control airspace. Phase I of the program is discussed in this paper.

PRODUCTS AND ACTIVITIES

The E-MSAW function will provide an alert to the controller of impending violation of airspace defined as hazardous for Air Traffic Control (ATC) operations. E-MSAW airspace will be adapted directly from the Minimum Vectoring Altitude (MVA) charts prepared by the facility's operations staff.

The Minimum Vectoring Altitudes are determined from considerations of the terrain, location of airways, radar and communications coverage.

E-MSAW airspace is defined subject to the following constraints:

1. Each ARTCC will have the capability of adapting a maximum of 200 E-MSAW areas, bounded by closed polygons.

2. Each E-MSAW area will be defined by at least three but not more than ten line segments. End points will be defined by latitude and longitude. An E-MSAW area may be defined within another E-MSAW area.

3. Each E-MSAW area will have a safe altitude associated with it, defined to the nearest 100 feet.

4. Each E-MSAW area may have up to ten airports associated with it.

The latter provision is made in the initial implementation to allow definition of airspace to eliminate departure and arrival flights near airports and airport complexes.

Coding of the E-MSAW function into the NAFEC version of NAS 3d2.4 with its Universal Data Set (UDS) commenced in March 1978 following approval of the Computer Program Functional Specifications (Reference 2) and the Program Design Specifications (Reference 3). An extensive test program will follow delivery of the computer program. NAS 3d2.4 is a duplicate of the NAS ATC Operational Computer Program that was in field use from March 1977 through March 1978.

Three test series will be conducted at NAFEC: Acceptance (Product Assessment) Tests by Computer Sciences Corporation, Design Evaluation Tests by the MITRE Corporation and ATC Application Tests by NAFEC.

Acceptance (Product Assessment) tests will verify the technical integrity of the E-MSAW function as to its compliance with design data contained in the approved Computer Program Function Specifications.

Design Evaluation tests will measure the performance of significant elements of logic which constitute the E-MSAW function, including a parametric performance analysis.

ATC application tests will emphasize controller-computer interface evaluation and will seek to establish the usefulness of the function from the point of view of the controller. Simulated operational testing will also be used to gain additional insight into the response time distribution for the computer-controller-pilot system when E-MSAW advisories are provided.

A NAFEC demonstration for the Operating Services will be given at the conclusion of the NAFEC Testing. Assuming a successful demonstration, the computer program will be integrated into the current system tape (NAS 3d2.8) for field evaluation at the key sites (Albuquerque and Memphis). The goal of the Phase I development program is the integration in the National Airspace System by release of NAS Model 3d2.9, with nationwide implementation in late 1979, as shown in Figure 1.

TECHNICAL APPROACH

The baseline system for developing the test, evaluation and demonstration of the E-MSAW function at NAFEC is NAS model 3d2.4. The E-MSAW function uses, as primary input, radar tracking data as computed and stored by the Automatic Tracking function (X,Y tracking) and the Altitude Tracking (Z tracking) function. E-MSAW processing sequences on a subcycle basis to operate after the tracking function has been completed, thus avoiding destructive

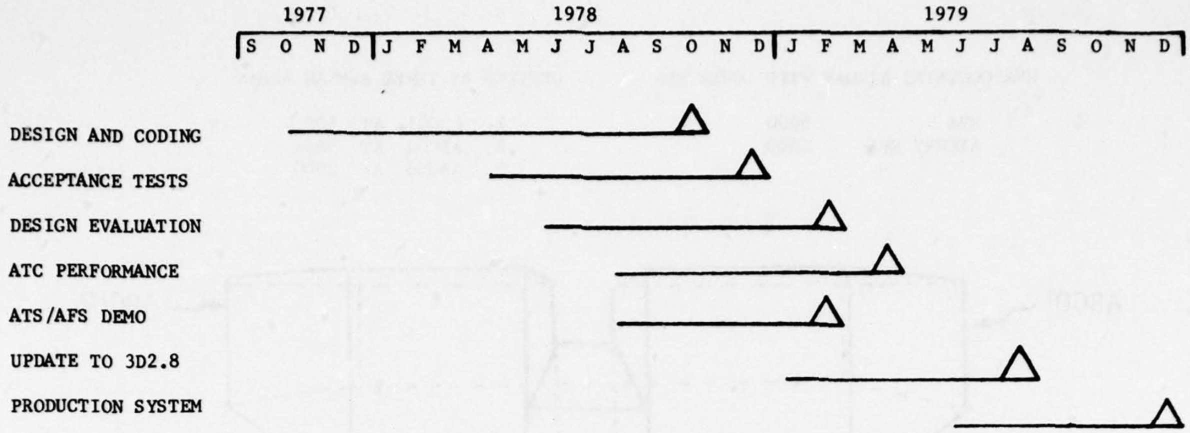


FIGURE 1, PHASE I DEVELOPMENT SCHEDULE

interference in accessing the tracking tables. The main body of the E-MSAW program will be required in core during each tracking subcycle (6 seconds) and so will be dynamically buffered.

a. Filter Design

A major technical problem addressed in computer program design relates to the efficient comparison of extrapolated flight paths for all eligible tracks with upwards of 2000 line segments defining the horizontal crossections of E-MSAW areas. In dealing with this problem, the technique employed is to apply filters of *increasingly finer mesh. The* E-MSAW function will operate periodically, inspecting the complete track file on a cyclic basis.

An adaptable High Gross Filter Altitude (HGFA) is specified.

This is an altitude high enough so that level, climbing and descending aircraft above this altitude would not be projected to enter any E-MSAW airspace within the filter processing time interval. At this first level filter, VFR flights will be screened out; i.e., flights with no assigned altitude and no filed flight plan. There will, however, be E-MSAW processing of VFR tracks which have a Mode-C reported or a controller-entered altitude, when the controller specifically requested it.

A middle gross filter altitude will be utilized, similar to the high gross altitude filter, to further reduce the E-MSAW processing load. The Middle Gross Filter Altitude (MGFA) is set at a lower level to screen out aircraft above this altitude for climbing and level flights and inspects them on the same periodic basis as indicated above for flights above the High Gross Filter Altitude (HGFA). At this level, however, descending flights could conceivably project into E-MSAW airspace before the next periodic inspection of flights *above* MGFA, *and* therefore, are candidates for further E-MSAW processing. (See Figure 2)

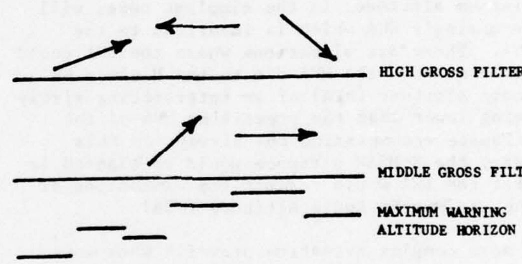


FIGURE 2, GROSS ALTITUDE FILTERS

To facilitate the comparison of track position and velocity with E-MSAW airspace, each 3-10 sided polygon, capped by a E-MSAW Warning Altitude (EWA) describing the airspace, will be related to the Radar Sort Box (RSB) grid by the off-line processing of the adaptation assembler. (See Figure 3).

Since it is assumed the center area shall be completely covered with EWA assignments, each RSB, the 16x16 nautical mile box used in radar/track correlation, must contain a minimum altitude, below which track projections may generate an E-MSAW alert. If, however, the aircraft's departure or destination point can be matched to an airport adapted to the E-MSAW area (i.e., the EWA), the alert is inhibited. An RSB can either be totally encompassed by one E-MSAW area, or be

MVA CONTAINS AIRWAY WITH LOWER MEA

MVA	5000
AIRWAY MEA	2000

DEFINED BY THREE E-MSAW AREAS

1. ABCO1 AT 5000
2. ABCO2 AT 5000
3. ABCO3 AT 2000

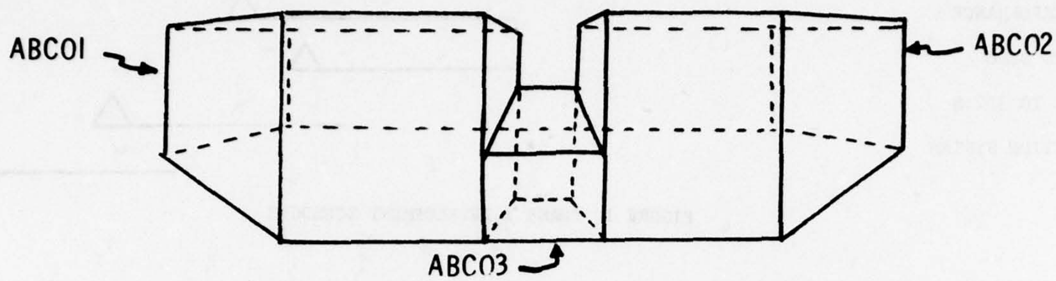


FIGURE 3, E-MSAW AREAS

intersected by one or more E-MSAW area boundaries, implying that several minimum altitudes prevail within the RSB. The adapted minimum altitude, in the simplest case, will be a single EWA which is identical to the MVA. There are situations where the EWA could be lower than the MVA due to the Minimum En Route Altitude (MEA) of an intersecting airway being lower than the prevailing MVA of the airspace encompassing the airway. In this case, the E-MSAW airspace would be adapted so that the EWA would reflect the dimensions of the Minimum En Route Altitude (MEA)

A more complex situation prevails when more than one E-MSAW area intersects within an RSB, meaning more than one EWA is associated with the RSB. This implies employment of a Maximum Warning Altitude (MWA) based on the higher EWA, for the sort box and some additional processing to detect the boundary where the EWA altitude changes and which EWA altitude applies to the current projected position of the candidate track. This additional processing is called area violation detection.

The gross filters described above are followed by an additional, finer filter known as the E-MSAW Sort Box filter. This filter serves to limit the number of E-MSAW areas, which must be examined for possible violations, to those areas which overlap the RSBs along the track's projected route of flight. The Minimum Track Altitudes (MTA) achieved by the altitude track for each sort box traversed in the lookahead time interval (VLAT, a parameter) are computed and compared to the maximum warning altitude stored by adaptation for each Radar Sort Box. If the MTA's are above these maxima for all RSBs traversed, the track is rejected from further processing. Otherwise, the polygons associated with the RSBs are examined for penetration by the track over the VLAT time interval. (See Figure 4)

Finally, if the track becomes eligible for an alert with an E-MSAW area that has an associated E-MSAW adapted airport list, then this list will be searched for a match with the associated arrival/departure points. If a match is found, then the alert is inhibited for the given E-MSAW area.

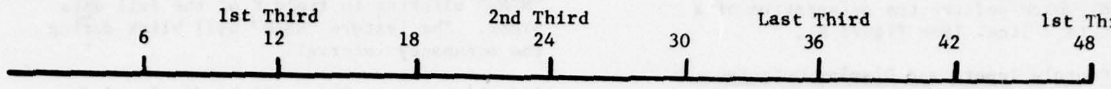
b. Processing Sequence

The total number of tracks are logically divided into subsets based upon an adaptable parameter, the High Gross Filter Interval (HGFI). Subsets are formed by considering only every HGFI (e.g., if HGFI=3, then every third) track and incrementing the first track on each execution by the HGFI filter. This results in examining 1/HGFI of all tracks every HGFI subcycle.

c. COMPOOL Table Design

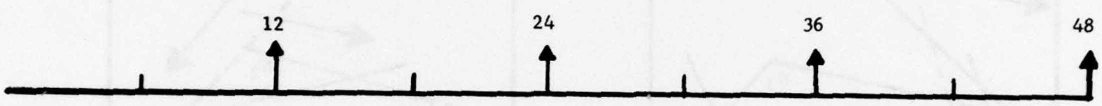
Processing efficiency is the main consideration in a table design that maps the polygons and their associated altitudes and airports into Radar Sort Boxes (RSB's). The tables contain pointers and are chained to permit rapid retrieval of polygon boundaries and to access switches which control the selection of three distinct violation detection algorithms designed to service specific RSB/polygon configurations:

High Gross Filter Frequency HGFF = 2 Subcycles
High Gross Filter Internal HGFI = 3



GROSS FILTER PROCESSING

Candidate Retest Filter Frequency CRFF = 2 Subcycles



RSB FILTER PROCESSING

FIGURE 4, E-MSAW PROCESSING SEQUENCE

1. Polygons with only convex angles in the RSB. (See Figure 5).

2. Polygons with only concave angles in the RSB.

3. Polygons with mixed concave and convex angles in the RSB. (See Figure 5).

Summarily, adaptation tables are constructed off-line by the Adaptation Control Environment System (ACES) to represent E-MSAW airspace mapped into RSB's by the following stored information:

1. The total number of the polygon line segments that intersect the RSB.

2. The polygon vertices which make up the line segments that intersect the RSB - defined in clockwise direction.

3. An indication whether the entire polygon is completely within the RSB.

4. The altitude associated with the polygon.

5. An indication of which algorithm applies to this polygon in this RSB.

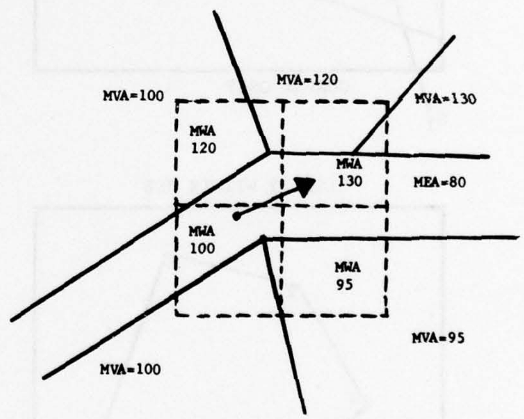


FIGURE 5, SORT BOX FILTER

If the maximum capability to adapt 200 polygons, each with ten vertices, is required, then a maximum of 15,000 words will be needed to map the polygons into the Radar Sort Boxes. These data will be stored on disk and buffered only when required by execution of the violation detection algorithms.

Information from the adapted tables can be rapidly retrieved by an initial, simple calculation to determine the RSB's intersected by the ground track of the aircraft. Determination whether the ground track will penetrate the E-MSAW polygon is facilitated by the definition of a basic procedure called ORIENT which defines the orientation of a point to a line. (See Figure 6).

d. <u>Console Inputs and Display Outputs</u>

Many of the console inputs, display routing and control parallel those of the En Route Conflict Alert function.

An alert will normally not be displayed on its first occurrence. An alert situation must be detected in two of three consecutive computation cycles to qualify for display. An Alert Redetection Validation Mask (ARVM) is the parameter which controls the display of alerts.

E-MSAW alerts will be displayed on the Controller's PVD by displaying the letters "MSAW" blinking in field E of the full data block. The letters "MSAW" will blink during the occupancy interval.

A double-written line will be displayed from the track position to the E-MSAW point of violation, at the end of which the altitude violated will be displayed.

When the conditions for alert are satisfied, the E-MSAW alert will be routed to the controlling sector and if the track is in

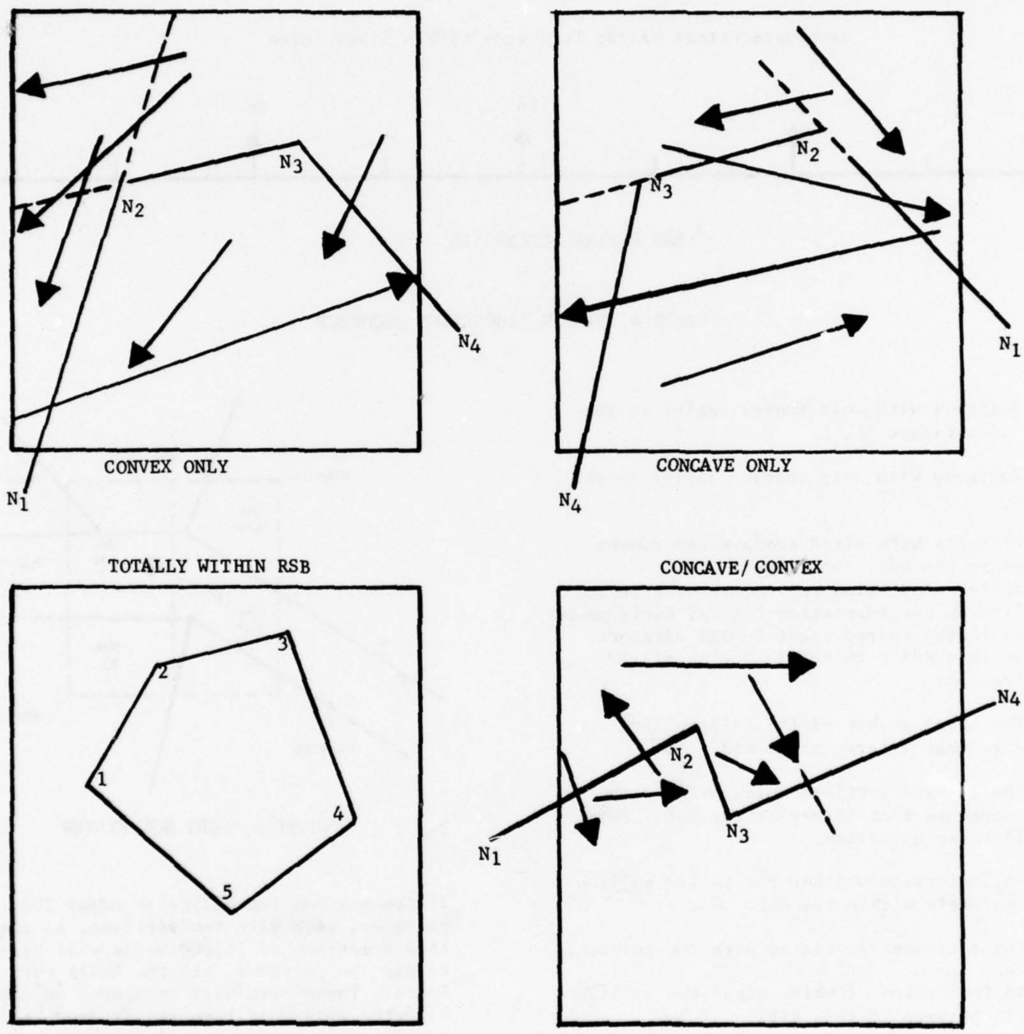


FIGURE 6, VIOLATION DETECTION ALGORITHMS

HANDOFF status, also routed to the receiving sector.

It will be possible by supervisory inputs to turn the E-MSAW function off for the entire Center or to turn off the display of alerts for an individual sector.

The controller will be provided with two types of suppression of individual alerts enterable from his console:

1. Alert Suppression will suppress display of an alert on a specific flight relative to a specific E-MSAW area. The letters MOFF would appear in field E of the data block. The suppression is discontinued on termination of the alert situation.

2. Indefinite Suppression will inhibit alerts on a given flight center-wide and indefinitely. The letters MIFF will appear in field E of the data block to remind the controllers of the action taken.

The Alert Suppression and Indefinite Suppression will be reversible actions. (See Figure 7).

SUMMARY

This effort will result in software for the enroute ATC computer system that will provide an automatic alerting capacity to alert the Air Traffic Controller when aircraft under his control is below or projected to go below a defined minimum safe altitude.

ACKNOWLEDGEMENTS

The E-MSAW development has required the skill, knowledge and participation of the Air Traffic Service, The MITRE Corporation, Computer Sciences Corporation, and NAFEC along with other elements of SRDS.

In the preparation of this paper, the assistance of Mr. Anthony Severino of ARD-140 and Mr. Stephen J. Hauser, Jr., of The MITRE Corporation is gratefully acknowledged.

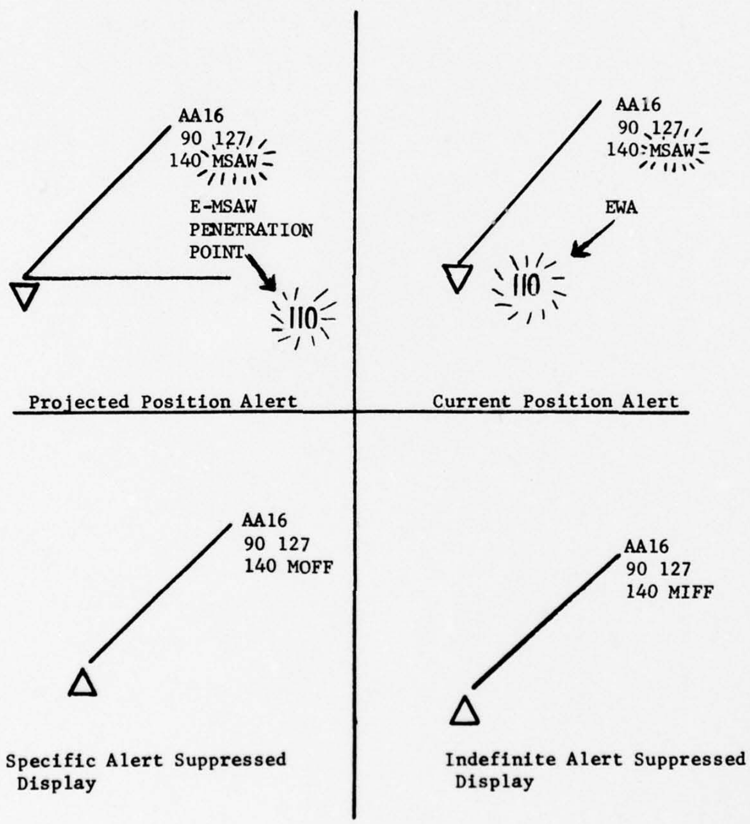


FIGURE 7, CONTROLLERS DISPLAY FORMAT OF ALERT

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1. Request for R, D, and E effort 9550-AAT-300-23, "Operational En Route Minimum Safe Altitude Warning System (E-MSAW)", February 1977.

2. Preliminary Computer Program Functional Specification (CPFS) for En Route Minimum Safe Altitude Warning (E-MSAW), (Revised March 1978).

3. Preliminary Program Design Specification (PDS) for En Route Minimum Safe Altitude Warning (E-MSAW), May 1978.

ELECTRONIC TABULAR DISPLAY SYSTEM (ETABS) DEVELOPMENT PROGRAM

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BIOGRAPHY

Donald L. Scheffler is a mathematician in the En Route Branch, ATC Systems Division, SRDS. He received his B.S. in mathematics in 1954 from the University of Chicago. Before joining the FAA in 1959, he spent 5 years at the Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland, where he worked on two of the early digital computers, EDVAC and ORDVAC. From 1961 to 1966 he was employed as a senior systems analyst with American Airlines and TRW. He rejoined the FAA in 1966 as Chief of the Computer Programming Section in the ATC Development Division where he headed the software development for the ARTS III Terminal Air Traffic Control System.

ABSTRACT

The state of development of the Electronic Tabular Display System (ETABS) development program is described. The object of the ETABS development program is to apply computer and electronic display technology in the replacement of the flight strip printers and paper flight progress strips now in use at all Air Route Traffic Control Centers (ARTCCs). Through the use of electronic displays, processors, and touch entry devices, ETABS will automatically provide non-radar flight and control data to the Data ("D") Controller at each en route control sector. It will also provide meteorological and other operational support data on the ETABS display. The need for manual handling and updating of the paper flight strips will be eliminated. The "D" Controller workload will be reduced with a consequent increase in controller productivity. The removal of flight strip printers will eliminate the need for the Assistant ("A") Controller position in the sector control team, thereby reducing the staffing requirements per sector.

BACKGROUND

Since the inception of the Air Traffic Control system, the method of posting flight data information to the air traffic controller has been the paper flight strip. Before the introduction of the present NAS Stage A ATC System, flight data information was entered and updated manually by pencil on the flight strip. The present system uses electro-mechanical flight strip printers which, under computer control, print initial and updated flight data on paper strips and distribute the strips to the proper sectors. This system requires mounting ("stuffing") of the strip by hand in the flight strip holders, placing the holders in the desired position in the flight strip bay, updating the flight data by pencil, and entering update information into the computer by means of a manually operated keyboard device. This is a cumbersome operation which consumes much of "D" Controller's and "A" Controller's time.

The existing sector in an Air Route Traffic Control Center is normally staffed by a two-person team comprising a Radar ("R") Controller and a Data ("D") Controller. Although this two-person team is the normal mode of staffing a sector, three-person teams are sometimes employed at certain sectors during periods of high traffic activity. In the three-person team an additional Tracker ("T") Controller performs manual operations and flight strip processing while the "D" Controller performs interphone communications and assists the "T" Controller. The two or three-person sector team is supported by an "A" Controller who mounts and delivers flight strips to

each sector team. One "A" Controller typically services two sectors.

At the current air traffic level, approximately 8,000 controllers are required to staff the existing sectors in the Air Route Traffic Control Centers. A recent study (Reference 1) indicates that with the forecasted increase in air traffic the controller staff will need to be increased significantly with the creation of new sectors (sector-splitting) which will be necessary to meet future traffic demands. The study shows that the implementation of ETABS will result in an increase in controller productivity with a consequent reduction in sector staffing growth rates. Based upon an ETABS implementation in the 1984-1985 period, present value cost savings through 1999 are estimated at $433.7 million.

Prior Activities

Starting in mid-1974, studies were conducted to define and develop concepts for the electronic display of flight plan data. Analytical studies were made of sector data requirements at several Air Route Traffic Control Centers. These studies were made by SRI International (formerly Stanford Research Institute), the MITRE Corporation, and the FAA's National Aviation Facilities Experimental Center (NAFEC).

In 1975 an experimental ETABS facility was established at the MITRE Corporation's Westgate Facility (see Figure 1) to study various data formats, data entry techniques, and operational design requirements. These experiments involved teams of operational air traffic controllers from 3 Air Route Traffic Control Centers. Basic software packages were developed to investigate tabular display design alternatives and human factor considerations. Other human factor aspects were evaluated at the NAFEC Computer Controller Interface Laboratory.

The result of this work was an Engineering Requirement (Reference 2) which was completed early in 1978. Reference 3 contains additional detail on earlier activities

PRODUCTS/EXPECTED RESULTS

In March the FAA issued a Request for Proposal on ETABS. Proposals were received from industry in May and at the time of this writing (June 1978) are being evaluated. A contract award is planned by November 1978. A schedule of major milestones is

FIGURE 1, EXPERIMENTAL ETABS FACILITY

presented in Figure 2. Approximately one year after contract award, an ETABS engineering model will be installed at NAFEC. This system will consist of two interface processors to provide a high speed redundant interface with the NAS En Route Central Computer Complex (CCC) and six sector positions, each consisting of an electronic tabular display, touch entry device, keyboard, and display processor to interface the sector with the interface processor. See Figures 3 and 4.

The ETABS Engineering Model will be designed to replace the present "D" sector position equipment at 6 of the 24 sectors in the NAS En Route Laboratory in the NAFEC System Support Facility and will perform all the functions of a full-scale ETABS system.

The ETABS Engineering Model will be evaluated and used to determine the effectiveness of:

1. The interface with the NAS En Route Central Computer Complex; that is, the integrity of the mutually interdependent hardware and software designs of ETABS and the Central Computer Complex.

2. The display formats on the electronic displays which will present flight plan data to the "D" and "R" Controllers.

3. The ease of controller data entry to the flight data base, primarily through the use of touch entry devices (activated by touching the display with a finger) and software controlled display selection lists to guide the controller.

4. The methods of transitioning into a facility operational state from the present manual flight progress strip methods in the field.

5. The fail-safe, fail-soft design with a non-volatile flight data display system in providing for continued operation during equipment failures.

a. Products:

The products resulting from the ETABS evaluation will be a comprehensive evaluation report and a technical data package. The evaluation report will contain:

1. A definition of modifications to

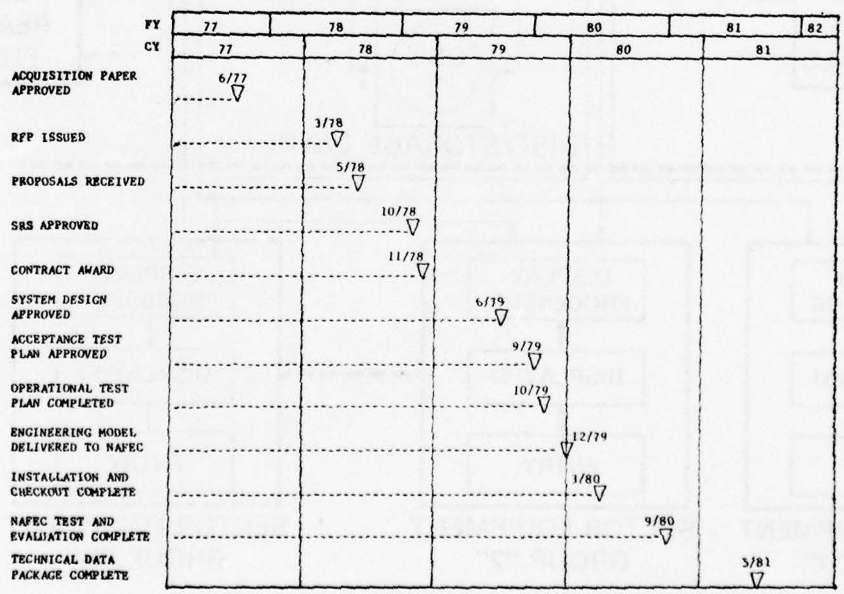

FIGURE 2, ELECTRONIC TABULAR DISPLAY SYSTEM SCHEDULE

the NAS En Route Central Computer Complex software needed to interface with ETABS.

2. The most effective methods for presenting flight plan data to the controllers and for providing access to the flight plan data base.

3. A method to effectively transition from the present manual flight progress strips to ETABS in an operational environment.

4. Methods to provide for continued operation during system compenent failures.

5. Validation of the ETABS Cost Analysis. (Reference 1)

The technical data package will contain the information and documents required by the Airway Facilities Service to prepare specifications for competitive procurement and implementation of a production version of ETABS.

Benefits

ETABS affects sector control operations by introducing more efficient means of processing data by automating current manual methods but will not affect surveillance, decision making, and air-ground communication requirements as currently conducted. Certain manual tasks will be eliminated and other tasks altered, which jointly affect sector team staffing requirements.

With the removal of the flight progress strip bay, all manual activities associated with flight strip processing will be eliminated. For example, the current task of hand-copying flight plan updates for

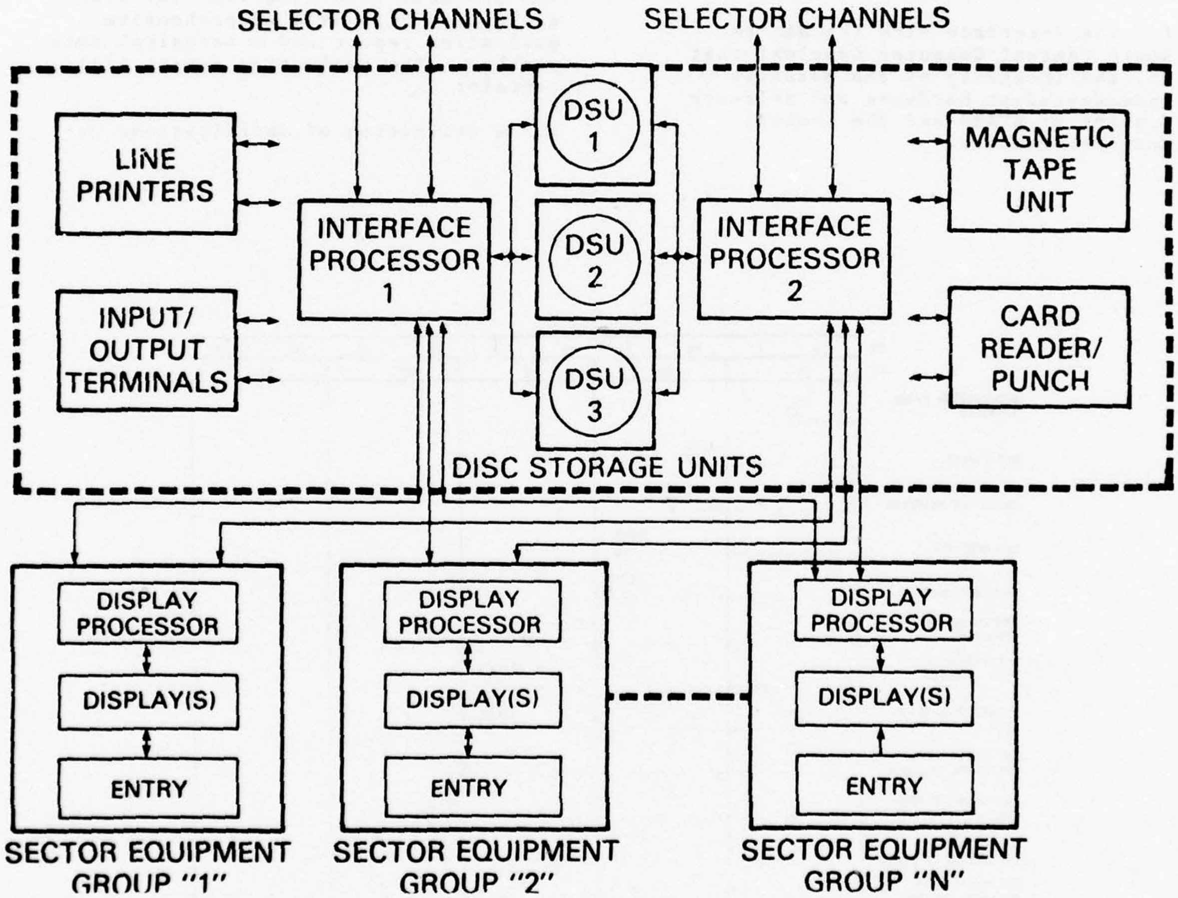

FIGURE 3, COMMON EQUIPMENT GROUP

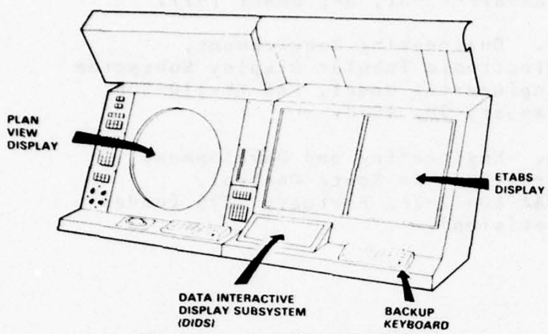

FIGURE 4, SECTOR WITH ETABS

the Computer Readout Device (CRD) onto proposed flight strips will be performed automatically by ETABS. In addition, an alert feature will be provided to attract the attention of the controller when there are flight plan changes or updates. Sequencing, arranging, and removing of flight data will be automatic. While these tasks may not seem intricate, they are now being performed manually and therefore consume controller's time. Elimination of mechanical tasks will enable the controller to spend more time with surveillance, decision making, and communications functions.

One important advantage of ETABS is that it can dynamically display to the "D" Controller the same type of "alerts" that are now displayed only to the "R" Controller. An example is the computer generated alert of an impending conflict between two aircraft which will be displayed on ETABS, as well as the Radar display, thereby enabling the "D" Controller to provide more assistance in resolving traffic control problems.

Controller work time required for handoffs and points will be reduced by ETABs. For example, automatic exchanges of flight plan data between tabular displays will eliminate the need for interphone communications which are currently needed to transmit such data as part of pointouts. The electronic display of these data will be effected more quickly than voice transmissions. ETABS will provide means for checking on the completion of important control actions (for example, issuance of radio frequency changes), and to alert controllers of the need to carry out such functions if they have been overlooked.

TECHNICAL APPROACH

ETABS will consist of the computer, display, and message entry resources necessary to support the en route sector positions. A distributed processing network concept will be used to accept, process, and distribute flight planning data to recipient sector positions and to accept, process, and transmit controller originated messages to the NAS En Route Central Computer Complex (CCC).

The primary ETABS computer resource will be Interface Processors interfacing directly with the CCC and with smaller display processors located of each sector position. Figure 3 illustrates an ETABS configuration consisting of redundant equipment within a Common Equipment Group and Sector Equipment Groups, one for each sector position. Reference 2 contains a detailed description of each ETABS component.

An ETABS hardware interface device connected to the Interface Processor will provide a communications path to the CCC Input/ Output Control Element (IOCE) and respond to commands from the CCC.

a. Common Equipment Group:

The common equipment group will be capable of performing the following functions while on-line:

1. Provide communications with the CCC.

2. Provide redundant storage of all operational flight and adaptation data.

3. Distribute data to and accept data from the Sector Equipment Groups.

4. Service requests from the Sector Equipment Groups, such as:

   a. Program load requests.
   b. Data base regeneration requests.
   c. Supplemental data requests.

5. Multiplex air traffic controller input messages from the Sector Equipment Groups to the CCC.

6. Provide intersector communications.

7. Generate hard-copy data via the line printers.

8. Provide configuration management of ETABS components including automatic reconfiguration of equipment following a system component failure.

9. Record performance and operational data on magnetic tape for later analysis.

10. Communicate with system operator through the Input/Output terminals.

The Common Equipment Group will be capable of performing the following functions while off-line:

1. Perform computer program compilations and assemblies for both the Interface and Display processors.

2. Run maintenance programs to diagnose faults in both the Common Equipment Group and the Sector Equipment Group.

3. Process simulation data from on off-line CCC configuration.

4. Perform assemblies of adaptation data and output adaptation sub-sets for use in the operational program.

b. Sector Equipment Group:

The Sector Equipment Group will be capable of performing the following functions:

1. Provide storage of air traffic control sector-related data base.

2. Format and display required portions of the data base.

3. Provide an interactive data entry capability.

4. Manage communications with the Interface Processor.

SUMMARY

The end product of the ETABS development program will be a specification for production system which will replace the paper flight strips used currently as part of the NAS En Route system to maintain and display flight plan data. ETABS will effectively automate some controller manual and verbal tasks, thereby reducing controller workload routinely required for each aircraft. The reduced workload per aircraft together with a redistribution of work among sector controller team members will enable sectors equipped with ETABS to handle more aircraft with fewer controllers than the same sectors using the present system with paper flight strips.

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EN ROUTE DISPLAY RECORDING/PLAYBACK

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BIOGRAPHY

Mr. Parker Harris, a registered professional engineer, is a Program Manager in the Systems Research and Development Service, ATC Systems Division. He has had extensive experience in the field of en route automation. Before joining the FAA in 1959 he was engaged in the design and testing of flight simulators with the Engineering and Research Corporation in Riverdale, Maryland.

ABSTRACT

The ability to record and later replay what had been seen on a controller's display has always been looked upon as a desirable goal. A number of experiments had been conducted in the past 10-15 years with this goal in view, but the equipment was usually unreliable, expensive, and the results of questionable value. Techniques previously used most often were either photographic film or analog TV video recording. Recently, however, technology has advanced to the point where equipment reliability is no longer a significant problem and high speed digital recording methods are able to produce acceptable results. A breadboard recording/playback system was designed and built by the FAA at the National Aviation Facilities Experimental Center (NAFEC). It had the ability to record and playback one display at a time. The breadboard model was highly successful and resulted in the FAA initiating the design and fabrication of an Engineering Model. The field or production version of this system will be modular and able to record 36 displays per module.

List of Acronyms

NAFEC	National Aviation Facilities Experimental Center
ATC	Air Traffic Control
SAR	System Analysis Recording
AFS	Aviation Facilities Service
SRDS	Systems Research & Development Service
ATS	Air Traffic Service
R&D	Research & Development
ARTCC	Air Route Traffic Control Center
RIB	Record Interface Buffer
HDDR	High Density Digital Recorder
EPIC	En Route Playback Interface Console
RIB	Record Interface Buffer
DCVG	Display Control & Vector Generator
DG	Display Generator
DGI/O	Display Generator Input/Output
PVD	Plan View Display (controllers display)
VAD	Valid Address
VCO	Voltage Controlled Oscillator
LPF	Low Pass Filter
D/A	Digital to Analog
SOD	Start of Display
EOD	End of Display
MUX	Multiplexer

BACKGROUND

Voice communications recordings has been employed for some time in the Air Traffic Control (ATC) system, and has proved to be a valuable tool in analyzing ATC events that have occurred in the system. As the current en route automation system has evolved, it has become evident that it would be useful to have additional recording of data within the automation system. At the present time much of the data contained in the automated system are being recorded via the System Analysis Recording (SAR) program. Although the statistical data collected by the SAR program are extensive, these recordings cannot be played back through a controller's display to

provide a composite, representation of what had previously been displayed to a controller, including weather, display off-set, data entry, etc. Recording of data in the display subsystem, with a selective play-back capability, has been suggested as a means of recreating the data that had been presented to a controller during some particular ATC related situation. The recordings could be replayed to give a visual presentation of the air traffic situation as it appeared on a controller's display at any given instant. When combined with SAR data and voice recordings this would provide a more complete reconstruction of a given traffic situation.

The FAA's intention to proceed with development of a method to record en route air traffic controller displays was contained in the 1973-1982 Ten-Year Plan, Appendix #2 and the Policy Summary, Appendix #1 of the same plan. However, even prior to this time both Air Traffic Service (ATS) and Airway Facilities Service (AFS) have requested Systems Research and Development Service (SRDS) to investigate the possibility of accomplishing display recording. In each case it was determined not to be practical at that time because of technological constraints.

More recent developments, however, in recording technology and availability of high speed solid state memories suggested that it had become practical to accomplish display recording. Accordingly, on May 5, 1975, ATS issued a Request for Research and Development (R&D) effort to determine if it was now feasible to record and playback controller display data. After surveying both Government and Industry and investigating various recording techniques and present technology, it was decided that a breadboard model be designed and built by the FAA to demonstrate feasibility. The breadboard model was successfully demonstrated in May 1977. Based on the success of the breadboard model, a decision was made in June 1977, to proceed with the development of an Engineering Model to be designed and fabricated in-house. The Engineering Requirement for the engineering model was completed in January 1978 and development of the engineering model was begun.

a. Products/Expected Results

After the development is complete, it is expected that a production procurement will be initiated to install this type of recorder at all ARTCCs. Some of the benefits to be achieved by this subsystem will be the ability to study and evaluate in detail air traffic conditions leading to ATC related situations. It can also be used as a maintenance tool to analyze reported discrepancies. Workloads and traffic delays may be studied. Also, it may be used in assisting and directing rescue operations.

An abbreviated schedule resulting in the first field installation is given below:

Preliminary Design Data
6/78
Engineering Model Fabrication Completed
1/79
Test and Evaluation Completed
7/79
Final Report
9/79
Technical Data Package to Airways Facilities Service
12/79
Projected Installation at First Center
6/82

TECHNICAL APPROACH

a. Design Criteria

The following design criteria were established as a result of coordination between the FAA Services. The engineering model is to be capable of meeting the following requirements.

1. Synchronize both voice and display recorder during playback.
2. High speed search of recorded tape in relation to a given time of day.
3. Simultaneous playback of two separate displays, without need for the ARTCC computer complex.
4. Duplicate the recorded tape for playback at other locations.
5. Record all data presented to the display.
6. Record all displays in any ARTCC. (Engineering Model will record all displays at NAFEC.)
7. Freeze mode available during playback.
8. Monitor any on-line display while recording.
9. Transparent to existing automation and display equipment and operation.

10. Operate with any of the ARTCC display channel configurations.
11. Recorders will operate in a sequential mode.
12. Each recorder will operate a minimum of four hours on a single reel of tape.

b. General System Description

The display data from each display will be sampled approximately once each second by a Record Interface Buffer (RIB) and will be recorded on one of two High Density Digital (HDD) Recorders. These will record for 4 hours each in an alternating mode. Presentation of recorded data will be accomplished by operating the recorders in a playback mode, through the En Route Playback Interface (EPI) to a standard display. A block diagram is shown in Figure 1.

The En Route displays are normally refreshed 55 times a second, and there is nominally one second between updates to the refresh data base. Most of the displayed data is redundant from a recording standpoint. Therefore, the design approach consists of storing on tape only one of the 55 identical display refresh frames which occur each second. The playback of the data requires a playback buffer EPI, a Display Control and Vector Generator (DCVG) and a display. A single refresh frame is transferred from tape to one of two semiconductor memories in the EPI. The frame stored in this memory is used to refresh a display at 55 frames per second. During this time, the next frame is transferred from tape to a second memory. Approximately every second, the two memories alternate between the modes of receiving data from tape and being used as a source of data for the display. This provides a playback presentation which is updated at the same rate as the original recorded data.

c. Record Function

1. DGI/O - DCVG Interface

Each Display Generator (DG) consists of a Display Generator Input/Output (DGI/O) assembly and six DCVGs. Each

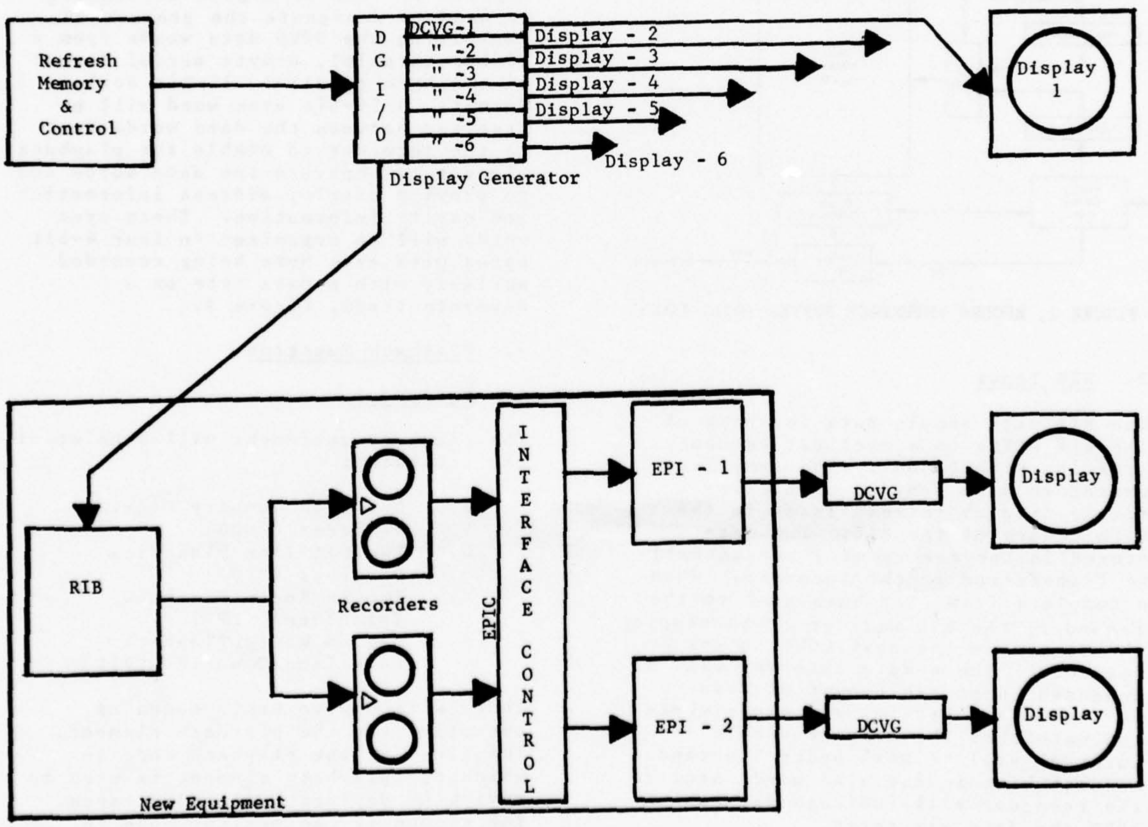

FIGURE 1, BLOCK DIAGRAM

DCVG drives one display. The DGI/O contains data reclocking logic, a DCVG address decoder, a blink clock generator, and the DCVG output multiplexers. A 16-line parallel data bus from the DGI/O is common to all six DCVGs. Valid Address (VAD) signals sent to each DCVG indicates which data words a DCVG may receive through the bus. The DCVG input data word is a 64 bit word consisting of four 16-bit bytes which is received by the DCVG at a data rate of 4.444 megabytes per second. The RIB, Figure 2, will obtain the necessary data and control signals from this interface.

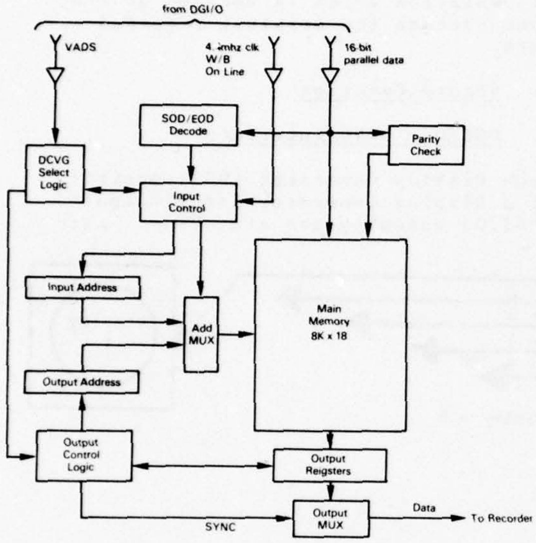

FIGURE 2, RECORD INTERFACE BUFFER (RIB) LOGIC

2. RIB Input

The RIB will sample data for each of the six DCVGs in a cyclical sequence starting with DCVG-1. The sampling procedure will consist of storing a single display refresh frame in the main memory of the RIB. The data stored in the memory will subsequently be transferred to the recorder. When a complete frame has been sent to the recorder, the RIB will go on to sample the data from the next DCVG in the sequence. The sample interval will be dependent upon the amount of data to be recorded. Preliminary experiments indicate that the average sample interval will be well under 1 second. Address bits in the sync words sent to the recorder will indicate from which DCVG the data was taken.

The main memory will operate on a first-in, first-out basis. The first data word written into memory will be the first word out during the read sequence. In this manner, the DCVG data words of the sampled refresh frame are written on to tape in the same sequence as they were sent to the on-line DCVG and display. To accomplish this, two 13-stage binary address counters will be used; one for the write address and the other for the read address. The appropriate counter is incremented for each byte written into or read out of memory. A multiplexer between the address counters and the memory, controlled by the input logic, determines which set of addresses are being used to access the memory. Both counters are reset prior to acquiring each refresh frame. Prior to reset, both counters should be at the address of the last data byte.

3. RIB Output

The 64-bit DCVG data words, which are stored in the RIB memory as four 16-bit bytes, will be turned 90 degrees by four parallel-in, serial-out registers called the output registers. The 90-degree terminology is used to designate the process of converting the DCVG data words from a 16-bit parallel, 4-byte serial format to a 4-byte parallel, 16-bit serial format. A 16-bit sync word will be inserted between the data words sent to the recorder to enable the playback element to separate the data words and to provide display address information and parity information. These sync words will be organized in four 4-bit bytes with each byte being recorded serially with a data byte on a separate track, Figure 3.

d. Playback Function

1. Equipment

The playback equipment will consist of the following:

a. One High Density Digital Recorder (HDDR)
b. Two Off-line Plan View Displays (PVD)
c. Two En Route Playback Interfaces (EPI)
d. One En Route Playback Interface Console (EPIC)

There will be two basic modes of operation for the playback element. The first is the playback mode in which the playback element is used to review or duplicate recorded tapes. The second is the monitor mode in

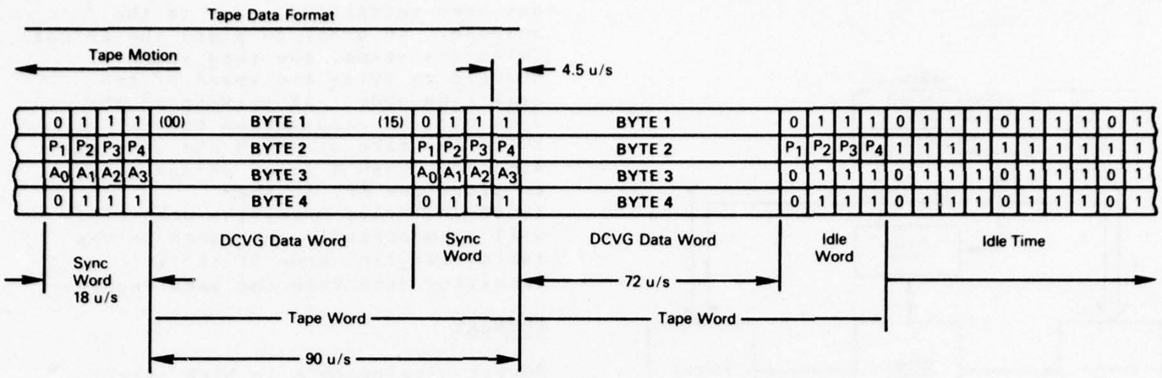

FIGURE 3, TAPE DATA FORMAT

which the playback element is used to visually monitor on a PVD the data as it is being recorded by the system. In the playback mode, it may be necessary to playback data from two displays simultaneously, as in the case of examining a hand-off situation. An operator will be able to control the operations of any recorder used in the playback mode. These operations include forward, fast forward, reverse, time code search, speed changes, and stop.

2. Time Synchronization of Recorders

Time synchronization of the digital recorders and the voice recorder on playback will be accomplished using a time code reader (Figure 4) to decode

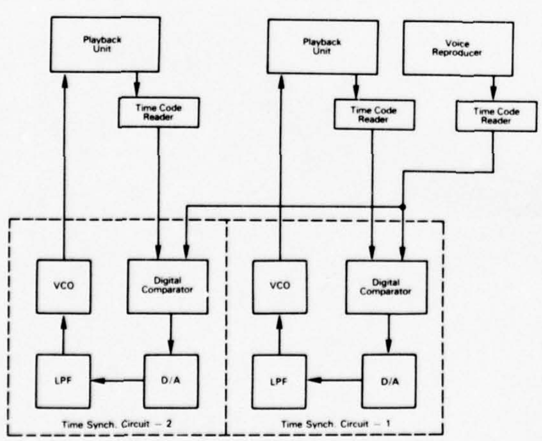

FIGURE 4, TIME CODE SYNCHRONIZATION LOGIC

time which will be recorded on a single track on each tape. One recorder will be used as a master unit with its speed controlled by its internal oscillator. All other recorders that are to be synchronized with this master unit will be set to ignore their internal oscillators on playback and to use an external reference signal to control their speed.

3. Data Format

The EPI is designed to allow the operator to designate the address of the display to be reviewed. The EPI will compare the incoming address with the selected address and accept data only when the addresses are equal. This address information will actually be used to designate one of the DCVGs within a DG. The DG will be designated by selecting the proper port using the multiplexing scheme previously described. Each port corresponds to one DG.

The data received from tape by the EPI will be stored in one of two semiconductor memories (Figure 5). When this memory has received a complete frame of data, the EPI will use the data to refresh the playback PVD via a DCVG. While the EPI is refreshing the display with data from the first memory (M1), it will simultaneously be storing the next frame of data from tape in the second memory (M2). When M2 has received a complete frame of data, the EPI will switch over to M2 for refreshing the display, while it proceeds to load the next frame into M1. The EPI alternates between M1 and M2 in this manner as long as data is being received from the recorder or until operator intervention. A memory is considered full when it has received a complete frame of data, even though the memory may not be physically

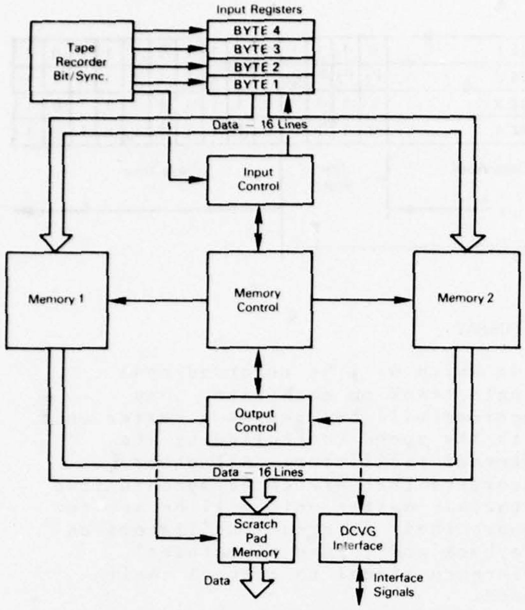

FIGURE 5, EN ROUTE PLAYBACK INTERFACE

filled to capacity. The EPI will alternate between memories (and between frames) at a rate which is equal to the sample rate used by the record element.

4. Playback Update Modes

The EPI will be designed to operate in three modes: real-time, freeze, and twice-real-time. In the real-time mode, the playback tape speed will be the same as the record tape speed, and the data will be read from tape at the same rate at which it was recorded. Therefore, the playback display will be updated at the same rate as the data was sampled by the RIB. In the freeze mode the EPI will be continuously refreshing the display from a single memory without alternating. When the operator initiates the freeze mode, the EPI will freeze the frame that is currently being used to refresh the display while it continues to load the other memory with the next frame sent by the recorder. Once an EPI is placed in the freeze mode, the operator may manually switch between the two memories and view each of the two frames stored for any length of time. When released from the freeze mode, the EPI will switch to refresh the display from the alternate memory. It will then proceed to load the next frame of data coming from the recorder into the memory from which it has been refreshing prior to the release. In order to place the EPI at twice-real-time, the tape speed is changed to twice the speed of the real-time mode. At this speed the data will be received by the EPI at twice the rate at which the data was sampled. When a speed change is made to place one EPI in the twice-real-time mode, the other EPI will automatically be placed in the twice-real-time mode if it is receiving data from the same recorder.

SUMMARY

Recent developments in high speed memories and high density digital recorders have made practical the design of display recording systems. Design concepts were tested and proven through the fabrication and testing of a breadboard model, which though limited in capacity, used the same techniques being incorporated in the engineering model. Following evaluation of the engineering model, procurement specifications will be written and production recording systems will be procured for installation at all en route centers. With the installation of this equipment the FAA will be in a better position to analyze and document various events occurring in the en route air traffic control system.

ACKNOWLEDGEMENT

The author would like to acknowledge the design efforts of Mr. Edwin A. Mack and Stephen D. Stratoti, ANA-140, who designed the breadboard model and provided much of the data contained in this report.

TERMINAL CONFLICT ALERT

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BIOGRAPHY

Gary Rowland, B.S.E.E., University of Maryland, 1970, is a member of Etta Kappa Nu. He has been employed by the Federal Aviation Administration for 7 1/2 years. Currently he is the Project Engineer for ARTS III Conflict Alert in the Terminal Branch of the Air Traffic Control Systems Division.

ABSTRACT

Although the safety record of the United States Air Traffic Control System is outstanding, the FAA has added a new function to its automated En Route and Terminal Control Facilities.

In this paper, a new Terminal Air Traffic Control (ATC) safety function called Conflict Alert, is described. A brief background of the evolution of the concept is provided along with details of the design of the automated functions. Features designed to control alert rates as a function of airport terminal area geography and control operations, are described. A brief summary and current deployment status is also provided.

BACKGROUND

The ARTS III terminal system, commissioned at 63 sites by 1973, provides an automation capability to the busiest instrument operations airports in the nation. By tracking the beacon reporting, controlled aircraft, the ARTS III system provides the controller with alphanumeric information such as aircraft ID (ACID), altitude and ground speed. This information is updated each radar scan and is displayed on the controller's display in a data block with a leader line pointing to the aircraft's radar/beacon return.

In 1975, a new terminal automation function, called MSAW (Minimum Safe Altitude Warning) was being field tested for ARTS III. To support this function, an altitude tracker, using altitude encoded Mode-C beacon returns, was added. When an aircraft was predicted to be in potentially hazardous proximity to a ground obstruction or predicted to be in such a situation in the near future, the controller would be alerted via a visual and aural alarm.

By 1975, FAA had also been experimenting with the idea of a conflict alert function for several years but had not planned to implement the capability before a more sophisticated radar beacon tracker was introduced. In late 1975, because of the availability in the ARTS III system of both the horizontal and altitude tracking functions, and the success in developing an En Route Conflict Alert function, it was decided to accelerate the schedule to implement a conflict alert function for the terminal environment.

The objectives of this development effort were to:

a. Increase air safety in the ARTS III Terminal Environment by detecting potentially hazardous aircraft pair encounters and providing an aural and visual alert to the controller with sufficient time to issue control instructions to the aircraft pilot if deemed necessary by the controller.

b. Provide this capability at the earliest possible date.

c. Provide this capability in a manner most useful to the controller (i.e., minimal nuisance alerts - no increase in workload).

d. Minimize the additional equipment required for the ARTS III system.

In order to meet the objectives, the following development guidelines were adhered to throughout the effort:

a. Use existing ARTS III hardware/software to maximum extent.

b. Merge Conflict Alert (CA) function with most current version of the operational ARTS III program, then handoff to operating services for implementation.

c. Limit aircraft eligibility to controlled aircraft with altitude reporting transponders.

In keeping with the development guidelines, single beacon Terminal Conflict Alert is limited to conflicts between two controlled, automatic altitude reporting aircraft. The

existing MSAW altitude tracker and aural alarm is used with the new conflict alert software module for ARTS III.

The conflict alert program was developed by the Sperry UNIVAC Corporation at Minneapolis and demonstrated at the National Aviation Facilities Experimental Center (NAFEC). Following the demonstration, the program was extensively tested at NAFEC by FAA and the MITRE/METREK Corporation. Following the NAFEC testing, the program was evaluated at the Houston, Texas ARTS III facility in a "backroom" mode (i.e., the CA function was cycling but was only visible on selected, non-operational displays). This evaluation period afforded an opportunity to locate program weaknesses, evaluate alert rates and alert distributions and to fine tune the system parameters.

Following the R&D effort, the Operating services evaluated the program with controller participation, and then the conflict alert capability was put into operational use in Houston in January 1978.

Products/Expected Results

The major accomplishments of the Terminal CA development effort are:

- Single Beacon Contractual Demonstration Complete 4/77
- Single Beacon Backroom T&E at Houston Complete 11/77
- ARTS III Conflict Alert Commissioned at 34 ARTS III Single Beacon
- Sites 7/78
- Dual Beacon contractual Demonstration Complete 3/78
- Dual beacon Backroom T&E at Miami Complete 7/78

The future milestones of Terminal Conflict Alert include:

- Dual Beacon Conflict Alert Commissioned at Miami ARTS III Site 9/78
- Conflict Alert Commissioned at all ARTS III Site 11/78

Technical Approach

Conflict Alert is a real time task called by the ARTS III Executive routine. It is performed once per sector (a sector is a 1/32 wedge of the full 360° scan of the radar) following the Tracking Prediction subroutine.

The CA control function performs certain routine "housekeeping" tasks (tasks that are only performed once per scan) and calls the primary filter which filters out those aircraft pairs (each conflict is evaluated on a pairwise basis) which could not possibly be in conflict during the next radar scan. The primary filter, in turn, calls the three conflict alert filters: LINCON (for linear predicted conflicts), MFMAMS (for maneuvering aircraft), and PROCON (a catch-all filter based on relative proximity of aircraft, largerly independent of aircraft velocity).

In order to concentrate on the conflict alert techniques used to detect potential conflict situations, we have simplified some important portions of the logic in this paper. Items which have been mentioned only briefly, or not at all, but which are nonetheless critical to the program include the following:

a. Airport Areas - It is realized that some form of program customizing is required in order to make conflict alert work in the terminal area with its dense, highly maneuvering traffic. Accordingly, each ARTS III coverage area (extending a radius of 60 miles from the antenna) is divided into 3 categories:

Type I Areas: The area which includes the terminal and the nearby airspace, adapted in the program as a convex polygon, limited in height.

Type II Areas: Attached to Type I areas extending out along adapted runway extension lines and limited in height.

Type III Areas: All airspace within radar coverage that is not designated as Type I or Type II areas.

Each different area may have different CA parameters. Thus, a different parameter set would be employed immediately around a busy terminal, as opposed to 30 miles away, where traffic is less dense and more predictable. In addition, certain branches of logic are only performed in certain areas (see PROCON In-line and Parallel). In this paper, unless noted otherwise, the general (Type III) area parameters are given whenever the CA logic is explained. The use of different airport areas enables each facility to tailor the program to its particular requirements. Figure 1 illustrates the concept.

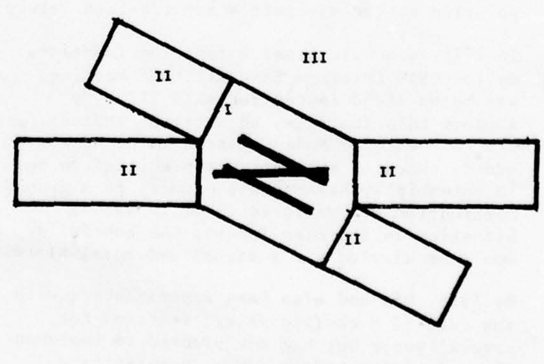


FIGURE 1, AIRPORT AREAS

b. Sliding Window Logic - In order to lend stability to the alerting functions, each conflict alert filter has an associated sliding window logic. This logic provides a built-in delay in the display of the conflict. For example, if the sliding window parameters are set for 2 out of 3, a single CA "hit" would not cause an alert. At least 2 hits out of the past 3 scans would be required. This is considered essential in the terminal environment in order to prevent annoying, short duration conflicts caused by maneuvering traffic. The values used in the various sliding windows currently are: LINCON (3 out of 5), MFMAMS (2 out of 3), and PROCON (1 out of 1 except for Constant Position Angle which is 2 out of 3).

c. Track Quality - Each CA filter has separate requirements for track firmness (a number assigned each track that is a function of its scan to scan correlation success), and data freshness (number of seconds since new report data has been received for a particular track). These qualities will affect the eligibility of a conflict pair for CA processing or (particularly in PROCON) which logic path is followed. PROCON also branches based on track stability (whether the track is considered to be in turn).

The heart of the conflict alert programs are the four filters:
Primary, LINCON, MFMAMS and PROCON. The filters work on aircraft pairs only (i.e., if aircraft A is in conflict with aircraft B, which is in conflict with aircraft C, the conflict encounters will be separately evaluated as two separate pair encounters: (1) A and B and (2) B and C. Each filter will be described in detail.

Primary Filter

If every possible pair involving eligible aircraft were separately evaluated, it would be necessary to perform $(n^2 - n)/2$ separate evaluations (n= number of eligible aircraft). For 100 aircraft, this would require nearly five thousand separate CA evaluations. Because this would overload the processor, a double-linked, projected X-thread list is employed as a primary filter. Under normal traffic distributions this filter will eliminate more than 90% of all possible conflict pairs, while passing any and all that might be eligible for alert during the next scan.

Each eligible aircraft is evaluated as its position and velocity is updated by tracking (in this paper, the complex problem of time correction is ignored - suffice it to say that the CA program does make the necessary corrections required to assure that each potential conflict pair is evaluated at a common time using the freshest available data).

The geometry of the primary filter is illustrated in Figure 2. Let the aircraft

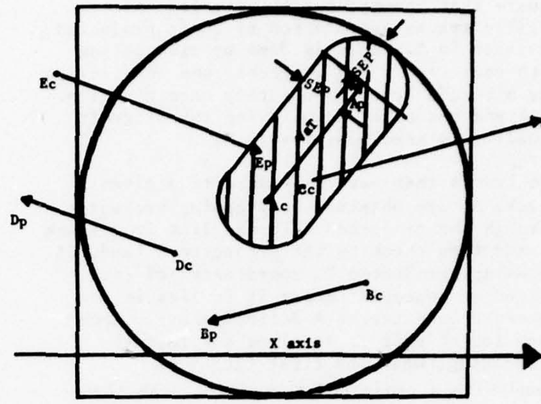


FIGURE 2, PRIMARY FILTER GEOMETRY

currently being evaluated (Aircraft A) be currently located at the center of the circle of radius VaT + SEP. Where Va = the speed of aircraft A in the horizontal plane, T = projection or lookahead time, and SEP = lateral separation parameter. The meaning of T and SEP will be clarified when we discuss the LINCON filter. Other aircraft in aircraft A's vicinity are shown as aircraft B, C, D and E. Each aircraft's current x, y position is identified by the subscript "C".

The circle in Figure 2 illustrates a basic area that, if searched about each eligible aircraft, will assure that all potential conflict pairs will be considered. We wish to protect aircraft A by warning of entry or predicted entry of other aircraft into the hatched area surrounding aircraft A's current to projected position vector $\overline{A_cA_p}$. This hatched area extends SEP nm in every direction from the vector $\overline{A_cA_p}$.

The circle of radius V_aT + SEP centered at A_c encompasses all T second projected positions of tracks that need to be retained for further
processing as potential conflicts with target A based on A's circle. It is to be noted that it is possible that a track can be in conflict with track A (See for example, target C in Figure 2) without having its projected position within the circle about A_c. Track C, however, will be passed as a potential conflict with track A when we consider all the projected track positions in track C's circle. In general, any track potentially conflicting with track A but not detected in the circle about A_c (that is, any track with an initial to projected position vector that intersects the hatched area surrounding $\overline{A_cA_p}$ and with a projected position lying outside A's search circle) will pick up track A's projected position within its own search

circle. Obviously, if this is true for the circle about A_c, it is also true for the square that encompasses the circle. All elgible tracks are ordered by their projected position in X. This is done by associating with each track, two numbers: one identifying the aircraft track immediately more negative in X and the other identifying the aircraft immediately more positive in X.

The tracks that have relevance to a given track, A, are obtained by stepping backwards through the projected X thread list from track A, and then checking the projected X (and, if necessary projected Y coordinate) of each target encountered to see if it lies in the square around target A defined above. Each such target pair is retained for further processing. When the first target is found with a projected X position less than X_{ac} -(VaT + SEP (i.e., outside the square to the left, such as aircraft D) we stop the search in the negative direction. We start again from A's projected X thread position and step forward in the thread performing the search as above. When the first projected position track is found to have its projected X coordinate greater than Xac + VaT + SEP (outside the square in the positive direction such as aircraft C) we stop the search and pass the potential conflict pairs on to the follow-on filters for more refined evaluation.

Inputs to Post-Primary Filters

The basic inputs to each filter are:

1. The track numbers of the two tracks to be processed.
2. The X and Y coordinates of the two tracks.
3. The X and Y components of velocity of these two tracks.
4. The Z coordinates for these two tracks.
5. The Z velocity for each track.
6. Timing data for each track (in order to evaluate the pair at a corrected time regardless of time of receipt of each target report).
7. In addition, certain filters require additional data such as altitude acceleration estimate (MFMAMS), and tracker turn indication (MFMAMS, PROCON).

Linear Conflict Detector (LINCON)

The purpose of LINCON is to determine if a conlict situation exists or will soon exist between a pair of tracks (aircraft) assuming they continue at their current speed and heading. LINCON is executed from the Primary Filter.

LINCON Description

Intervals of Conflicts - A conflict situation is determined by first evaluating an altitude interval of conflict based on current and predicted altitude. The time at which the 2 aircraft are predicted to first become in conflict in altitude is the left end of this time interval and is called AL1. If this number is negative, it is set to 0. The time at which the aircraft pair leave the altitude conflict (and become not in altitude conflict) is the right end of this time interval and is called AL2. If this number is negative, no altitude conflict exists and the track pair cannot be in conflict.

Next, a lateral conflict interval is determined. The time at which the two tracks are predicted to first come in lateral conflict is the left end of this time interval and is called LAT1. The time at which the tracks are predicted to leave the conflict area is the right end of this time interval and is called LAT2.

If the intersection of these two time intervals is non-zero, then the larger of the numbers AL1 and LAT1 is the time at which the track pair first will come into altitude and lateral conflict concurrently. This number is called the time of violation (TOV) and if TOV is less than or equal to the lookahead time, then a conflict exists or will exist within this time and the controller must be alerted.

Altitude Dimension - Let the 2 aircraft being considered be designated as aircraft A and aircraft B. Let aircraft A be at altitude Z_1 with an altitude change rate of $\dot{Z}_1$. Similiarly let aircraft B be at altitude Z_2 with an altitude change rate of $\dot{Z}_2$.Let

$\Delta Z = Z_2 - Z_1$,
$\Delta \dot{Z} = \dot{Z}_2 - \dot{Z}_1$, and
$Z_t = \Delta Z$ at some variable time t.

Then the altitude difference between the two aircraft at some variable time t is given by the equation

$\Delta Z_t = \Delta Z + \Delta \dot{Z} t$

Solving for t we get

$$1)\ t = \frac{\Delta Zt - \Delta Z}{\Delta \dot{Z}}$$

The minimum safe altitude between 2 aircraft is denoted by ZALQ. The time at which the 2 aircraft will be separated in altitude by distance ZALQ (altitude separation parameter) is obtained by substituting ZALQ for Z_t in equation 1).

$$2)\ t_{ZALQ} = \frac{ZALQ - \Delta Z}{\Delta \dot{Z}}$$

Recognizing the fact that the aircraft may be plus or minus ZALQ feet apart depending on which aircraft we designate as aircraft A and also the fact that the time so calculated may be the time of ZALQ separation diverging or ZALQ separation converging, we change equation 2) to:

$$t_{ZALQ} = \frac{\pm ZALQ - \Delta Z}{\Delta \dot{Z}}$$

This gives two valuse of t_{ZALQ}. The smaller of these values is the time of ZALQ foot separation when converging which we call the time of altitude violation when converging (TAVC).

$$TAVC = \frac{\pm ZALQ - \Delta Z}{\Delta \dot{Z}} \quad \text{Smallest value}$$

The larger of these values is the time of altitude violation when diverging (TAVD).

$$TAVD = \frac{\pm ZALQ - \Delta Z}{\Delta \dot{Z}} \quad \text{Largest value}$$

AL1 is set equal to TAVC unless TAVC is negative in which case AL1 is set to zero.

The time at which the 2 aircraft are at the same altitude is called the Time of Co-Altitude (TOCA) and is obtained by setting Z_t to zero in equation 1) Thus,

$$TOCA = \frac{-\Delta Z}{\Delta \dot{Z}}$$

The aircraft pair are coverging in altitude up until time TOCA and then they begin to diverge. A conflict situation can be considered to still exist for some period of time after they begin to diverge. For this reason AL2 is set equal to TOCA + ADAQ (TOCA-TAVC) where ADAQ is the altitude divergence allowance, a value that specifies the amount of time after the point where altitude divergence begins during which tracks should still be considered in conflict, expressed as a fraction of the TAVC-TOCA interval. Figure 3 should facilitate the understanding of the quantities just defined.

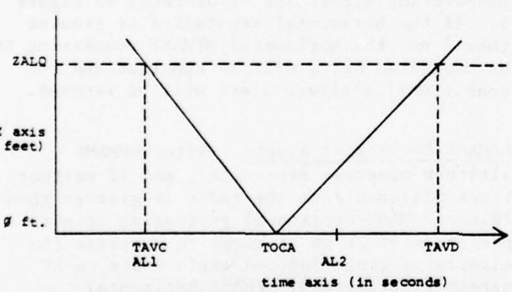


FIGURE 3, ALTITUDE CONFLICT INTERVAL

If $\Delta \dot{Z} = 0$, the aircraft are flying parallel in altitude and the equations for TAVC and TOCA do not apply because of a zero denominator. In fact, when $|\Delta \dot{Z}|$ is small, TAVC and TOCA are very sensitive to a small change in an altitude velocity component. Thus, a small change in $\Delta \dot{Z}$, which might be due to noise, could result in a very large change in TAVC or TOCA. For this reason, if $|\Delta \dot{Z}| \leq 5$ft./sec., the aircraft pair is considered parallel in altitude. In this case, if $\Delta Z \leq$ ZALQ, the tracks are considered to be in perpetual altitude conflict, and AL1 is set to 0 and AL2 is set to 900 seconds. Theoretically, AL2 should be set to $+\infty$ but 900 seconds is large enough to catch any concurrent lateral conflict if we assume that the LookAhead Time is less than 900 seconds.

If $|\Delta Z|$ is greater than ZALQ, the tracks are considered in perpetual non-conflict in altitude.

If $|\dot{Z}|$ for a track is less than 5'/sec., it will be set to 0 for all Conflict Alert calculations. The reasoning is that if the ascent/descent rate of a track is very small, the track is most likely in a level flight.

<u>Lateral Dimension</u> - In the XY plane, consider aircraft A at position A1 and aircraft B at position B1 and the aircraft heading in the direction of the arrows in Figure 4.

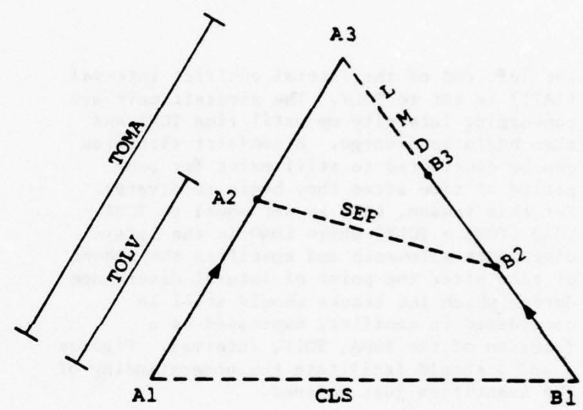


FIGURE 4, LATERAL CONFLICT ENCOUNTER

The current distance between the aircraft is called the Current Lateral Separation (CLS). If both aircraft proceed with their current speed and heading, then at some time in the future, aircraft A will be a position A2 and aircraft B will be a position B2 such that the distance between them at this time will be exactly SEP miles, where SEP is the minimum safe lateral separation.

The time it takes for the aircraft to get to these positions is called the Time of Lateral violation (TOLV). If the aircraft continue to proceed at their current speed and heading, they will at some time in the future be at positions A3 and B3 such that the distance between them is as small as it is ever going to be. That is, at this point they will begin to diverge laterally. This time is called the Time of Minimum Approach (TOMA) and the distance between them at this time is called the Lateral Miss Distance (LMD).

Let aircraft A have coordinates (x_1, y_1) and velocity components $(\dot{x}_1, \dot{y}_1)$.

Let aircraft B have coordinates (x_2, y_2) and velocity components $(\dot{x}_2, \dot{y}_2)$

Let- $X = X_2 - X_1$ and $Y = Y_2 - Y_1$

$$\dot{X} = \dot{X}_2 - \dot{X}_1 \text{ and } \dot{Y} = \dot{Y}_2 - \dot{Y}_1$$

Then CLS, TOMA, LMD, and tOLV are given by the following formulae:

$$CLS = (\Delta x^2 + \Delta y^2)^{1/2}$$

$$TOMA = -\frac{\Delta x \Delta \dot{x} + \Delta y \Delta \dot{y}}{\Delta \dot{x}^2 + \Delta \dot{y}^2}$$

$$LMD = \frac{|\Delta y \, \Delta \dot{x} - \Delta x \Delta \dot{y}|}{(\Delta \dot{x}^2 + \Delta \dot{y}^2)^{1/2}}$$

$$TOLV = \frac{-(\Delta x \Delta \dot{x} + \Delta y \Delta \dot{y}) - \sqrt{SEP^2 (\Delta \dot{x}^2 + \Delta \dot{y}^2) - (\Delta x \Delta \dot{y} - \Delta y \Delta \dot{x})^2}}{\Delta \dot{x}^2 + \Delta \dot{y}^2}$$

The left end of the lateral conflict interval (LAT1) is set to TOLV. The aircraft pair are converging laterally up until time TOMA and then begin to diverge. A conflict situation can be considered to still exist for some period of time after they begin to diverge. For this reason, LAT2 is set equal to TOMA + LDAQ (TOMA - TOLV) where LDAQ is the lateral divergence allowance and specifies the amount of time after the point of lateral divergence during which the tracks should still be considered in conflict, expressed as a fraction of the TOMA, TOLV, interval. Figures 4 and 5 should facilitate the understanding of the quantities just defined.

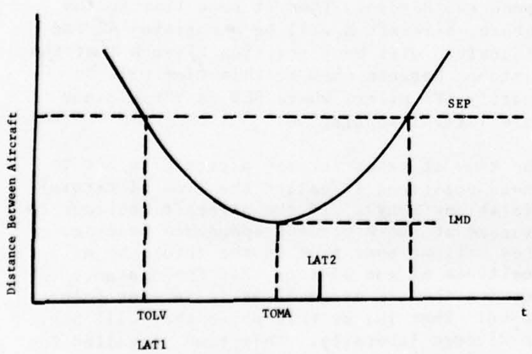


FIGURE 5, LATERAL CONFLICT GEOMETRY

If the track pair are traveling parallel or nearly parallel with equal or nearly equal speeds, the quantities TOLV and TOMA are very sensitive to small changes in speed or heading. For example a small change in x in one of the track pairs could change the tracks from coverging laterally to diverging laterally. This small change in $\dot{x}$ could be due merely to errors in the sensors. Such a track pair might go in and out of conflict from scan to scan due to this small change. To avoid this situation, special logic is added to handle the situation. The "slow closing" of a track pair can be measured by the quantity Relative Speed (R) given by the formula $R^2 = \Delta \dot{x}^2 + \Delta \dot{y}^2$.

The smaller the value of R, the more "slow closing" the track pair. If $R \leq 20$ knots, the tracks are considered "slow closing" and are declared in perpetual lateral conflict if CLS $\leq$ SEP. If CLS $>$ SEP, the tracks are considered in perpetual non-conflict horizontally.

Maneuver Filter (MFMAMS)

MFMAMS Altitude Alerts - With altitude separations of about 500 feet common--as between VFR and IFR traffic--altitude maneuvers of aircraft with close horizontal separation must be detected as early as possible, consistent with false alarms. As such, MFMAMS will check for hazardous altitude maneuvers on aircraft pairs which are within 2000 feet and "converging" in altitude or pairs which are within 1200 feet even though a "significant" altitude convergence rate is not noted. (An altitude convergence rate greater than 3 ft./sec. is considered significant).

An altitude maneuver for a given track is determined by examining the altitude acceleration estimate of the altitude tracker and will generate a conditional altitude alert "hit" if the maneuver has a magnitude greater than .5ft./sec.^{2} and is directed toward the other member of the pair. MFMAMS altitude maneuvering alerts are illustrated in Figure 6. If the horizontal separation is greater than 3 nm, the horizontal MFMAMS processing to be described below will be bypassed and the conditional altitude alert will be removed.

MFMAMS Horizontal Alerts - After MFMAMS altitude maneuver processing, and if neither track distance from the radar is greater than 28 nm (MFMAMS horizontal processing is not performed at 28 nm in range to suppress the effects of range induced angle noise on XY maneuver estimates), MFMAMS horizontal processing is performed.

If neither track is noted to have a left or right turn bit set, no further horizontal maneuver hazard processing will be performed and no horizontal MFMAMS hits will be generated. (The turn detection process, like all of conflict alert is performed in radar centered tangent "ground" plane coordinates.) The cross track deviation, with respect to the tracks tangent vector, valid two scans before is compared to a 1/5 nm threshold. If this cross track deviation -- the deviation

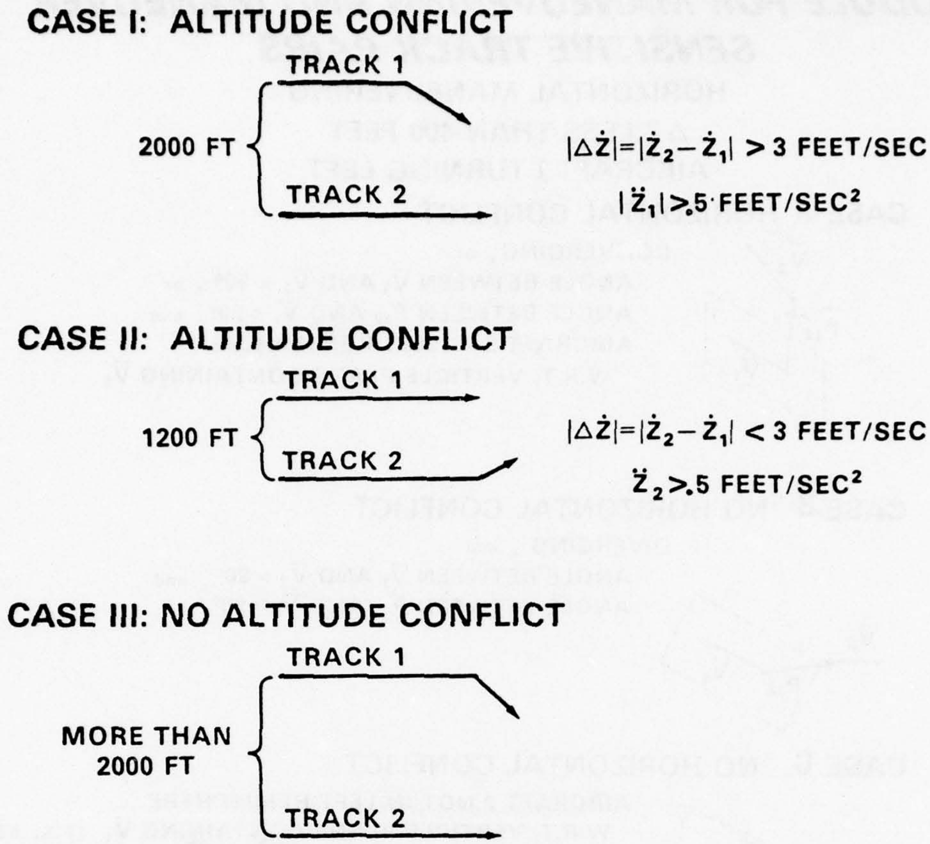


FIGURE 6, MFMAMS ALTITUDE MANEUVERING

component perpendicular to the above tangent vector -- exceeds the 1/5 nm threshold, the appropriate left/right turn bit is set.

If either track has a turn bit set, MFMAMS will process the pair as described below to try to estimate if the maneuver is hazardous.

First, the pair's altitude track separation is compared with a threshold parameter set at 400 ft. If the altitude separation exceeds 400 ft., no horizontal MFMAMS hits will be generated. If the pair's track altitude separation is less than 400 ft., the maneuver hazard in the horizontal plane will be estimated.

The horizontal maneuver hazard estimation is a several step process. First, a check is made to see if the track pair is diverging in the horizontal plane. The divergence measure used here is the sign of the vector dot prouct:

$$\vec{P} \bullet \vec{V} = \text{sign}\ (\Delta X \Delta \dot{X} + \Delta Y \Delta \dot{Y})$$

If $\overrightarrow{\Delta P} \cdot \vec{V}$ is negative the pair is judged to be converging. If positive, diverging. If diverging, a second check is made to see if the angle between the two track velocity vectors (track directions) is greater than 90°. We are referring here and in the next test to the magnitude of the smaller angle made between the positive directions of the two vectors. Thus, the check is to see if this smaller angle is of magnitude greater than 90°. If this angle is greater than 90°, a check is made to see if the angle between the relative position vector ($\overrightarrow{\Delta P_{12}} = P_2 - P_1$) and the velocity vector of the maneuvering track is greater then 90°. A negative result on any of the above three checks stops the checking and causes the horizontal maneuver pair relative hemisphere calculations described below to be performed. However, if the above three checks all produce positive results, it is judged that the given track's maneuver will not present a hazard for the pair. A check is made to see if this is the only maneuvering track in the pair. If not (that is, if there is a turn bit set for the other track) the last three checks are rerun. The check for the angle between the relative vector and its heading is here made using $\overrightarrow{\Delta P_{12}} = -\overrightarrow{\Delta P_{21}}$ and replacing $\overrightarrow{V_1}$

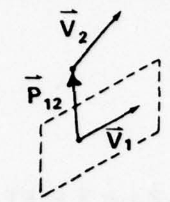
MODULE FOR MANEUVERING AND MANEUVER SENSITIVE TRACK PAIRS

HORIZONTAL MANEUVERING

ΔZ LESS THAN 400 FEET

AIRCRAFT 1 TURNING LEFT

CASE A HORIZONTAL CONFLICT



CONVERGING, or

ANGLE BETWEEN $\vec{V}_1$ AND $\vec{V}_2 < 90°$, or

ANGLE BETWEEN $\vec{P}_{12}$ AND $\vec{V}_1 < 90°$, and

AIRCRAFT 2 IN LEFT HEMISPHERE

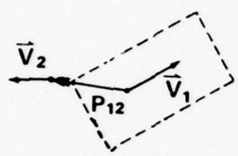
W.R.T. VERTICLE PLANE CONTAINING $\vec{V}_1$

CASE B NO HORIZONTAL CONFLICT

DIVERGING, and

ANGLE BETWEEN $\vec{V}_1$ AND $\vec{V}_2 > 90°$, and

ANGLE BETWEEN $\vec{P}_{12}$ AND $\vec{V}_1 > 90°$



CASE C NO HORIZONTAL CONFLICT

AIRCRAFT 2 NOT IN LEFT HEMISPHERE

W.R.T. VERTICLE PLANE CONTAINING $\vec{V}_1$ (I.E. AIRCRAFT Is Left turn bit is set but $\vec{P}_{12} \times \vec{V}_1$, Is Negative)

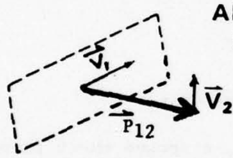


FIGURE 7, MFMAMS MANEUVERING HORIZONTAL

with $\vec{V}_2$. Figure 7 (A) illustrates a case for which the maneuver pair geometry will be calculated. Figure 7 (B) illustrates a case which the above three tests would judge not hazardous.

The MFMAMS horizontal maneuver pair relative hemisphere calculation is illustrated in Figure 7 (C). In this checking, if the cross product of the relative position vector $\Delta\vec{P}_{12}$ and the maneuvering track's velocity vector ($\Delta\vec{P}_{12} \times \vec{V}_1$ in Figure 7c) is positive and the maneuvering track's right turn bit is set, a MFMAMS hit will be set for the pair. (The sign of $\Delta P_{12} \times \vec{V}_1$ will be positive if track 2 is the right hemisphere with respect to a vertical plane through (X_1, Y_1) and parallel to $\vec{V}_1$ viewed in $\vec{V}_1$'s direction of motion).

At this point, if track 1 is the reference maneuvering track and no hit has been generated yet by the above process, a check is made to see if track 2 has a turn bit set. If so, the above process is repeated beginning with the examination of the horizontal divergence/convergence of the pair.

Proximity Filter (PROCON) Description

PROCON is designed for special cases in which an aircraft pair in potentially hazardous proximity may not be provided with a LINCON alert. Such a situation might arise when one of the aircraft making up the conflict pair is a new track with a track history insufficient to provide a reliable projected position or when the LINCON filter is not used because of the high nuisance rate expected in an area of extremely high aircraft meneuvering and density (such as a Type I area).

A track pair passed on to PROCON by the Primary Filter will first be examined for

altitude separation. If the altitude separation is less than 375 feet or if it is between 375 feet and 650 feet and converging in altitude by more than 3 feet/second, a check on their horizontal separation is made. If their horizontal separation is less than 3/4 nm, a Basic Proximity Conflict Alert is issued. Certain Type II airport areas are designated as parallel approach areas. As described below, aircraft pairs determined to be in one of these areas pass through special logic for purposes of minimizing nuisance alarms. If the aircraft is determined to be in a Type II area and the horizontal separation is less than $1/\sqrt{3}$ n.m., a Basic Proximity Alert is held as conditional pending analysis to determine if the pair is making an acceptable approach for the designated parallel approach adapted area.

The Proximity processing for approaches is a several step process.

First, the candidate aircraft pair is checked to see if the directions of flight are approximately parallel. This is done by examining the cosine squared of the angle between their horizontal velocity vectors. When this cosine squared value is greater than .98 the tracks are judged to be moving along approximately parallel lines. (This allows about an 8^o angle between the lines). For those tracks that are on approximately parallel paths, a further check is made to see if these lines are approximately parallel to the stored approach heading for the given type II airport area. If not, we either issue any pending conditional Basic Alerts or if there are none we classify the pair as ordinary and process accordingly. (See Ordinary below). If the headings agree with the stored approach headings, the tracks are further checked to see what their "parallel" separations are. These are obtained using the cross product relation

$$PSEP_1 = \frac{(\overrightarrow{\Delta P_{12}} \times \overrightarrow{V_1})_2}{|V_1|^2} = \frac{(\Delta P_{12} \times V_1)^2}{V_1^2}$$

which gives the parallel separation squared. This is checked by also using track 2's velocity data. If these parallel separation values are each less than $(1,000 \text{ feet})^2$ the tracks are classified as type II parallel.

In Line Type II track pairs are first checked to see that they are going in the same direction. Then their separation, $|\overline{P_{12}}|$, is compared to the stored In Line separation parameter for the given type II area, nominally 1/2 nm. If $|\overline{P_{12}}|$ is less than the corresponding threshold, a Promimity Alert is issued. If $|\overline{P_{12}}|$ is greater than the threshold but less than 3/4 nm, the pairs horizontal convergence rate is checked using the measure

$$\frac{(\Delta X \Delta \dot{X} + \Delta Y \Delta \dot{Y})2}{|P_{12}|} \quad \text{sign} \quad (\Delta X \Delta \dot{X} + \Delta Y \Delta \dot{Y})$$

If this shows a convergence rate of more (negative) than $-(60 \text{ knots})^2$, a Proximity alert is issued. (This measure avoids the use of a square root.)

For pairs that are classified as Parallel Type II pairs, we first check to see if the given Type II area expects parallel approaches (or departures). If so, a check is made to see if opposite direction parallel flight is involved, and if so, if this is allowed for the given type II. Next, the parallel separation of the pair is compared to a threshold value. This Parallel Threshold depends on the parallel approach (runway) separation. If the parallel separation is less than the allowed separation, an alert is issued.

Ordinary Processing is the last type of Proximity Processing. Reviewing what has gone before, we note that track pairs were classified for Ordinary Proximity Processing if they did not have a Basic Proximity Alert issued for them, or if they were in a Type II area, were not classified as In Line or Parallel and did not have a Conditional Basic Proximity Alert pending. Each pair classified for Ordinary Processing will recieve either or both of two types of processing. The first type is a threshold or threshold convergence type analogous to the In-Line processing above. Now, however, the pair can be from any type airport area. Nominally the corresponding separation threshold for ordinary pairs is 3/4 nm. The second threshold value is 1 nm. The convergence threshold is nominally $-(90 \text{ knots})^2$ and is applied with the second horizontal threshold, above.

The second part of the Ordinary Proximity processing provides a type of prediction. This logic uses a scan to scan comparison of the sine squared of the relative position angle,

$$\frac{(\Delta Y_{12})^2}{|\Delta P_{12}|^2} \quad \text{sign} \quad \frac{(\Delta Y_{12})^2}{\Delta P_{12}^2}$$

See Figure 8.

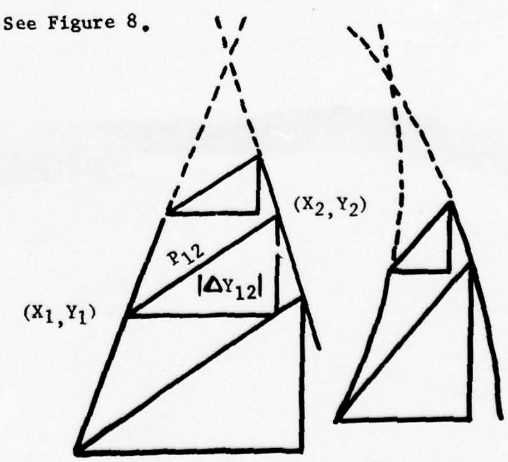


FIGURE 8, CONSTANT RELATIVE POSITION ANGLE GEOMETRY

(For constant speed straight line tracks this process involves the concept of "constant look angle"). If separation and convergence criteria are met and if the value of the above expression on the current scan is within a parameter (variable) value of the previous scan's value, a Proximity hit is generated for the current scan.

SUMMARY

Conflict Alert is a complex new ARTS III terminal automation function designed to assist the controller is doing his job. It is not designed to remove or reduce any of his responsibility, nor is it a tool to monitor his performance. It is being deployed at all of the ARTS III terminal control facilities, and it has been well received at those facilities where it is currently commissioned.

The Systems Research and Development Service is continuing development of enhancements to the program which will be introduced in an evolutionary manner so as to continue to diminish the likelihood of a mid-air collision involving a controlled aircraft.

REFERENCES

Design Data for Conflict Alert Stage I, Final-Revised May 1977. Sperry UNIVAC Report #ATC-10410.

ACKNOWLEDGEMENT

The Conflict Alert design described in this paper was accomplished by the Sperry UNIVAC Corporation under contract to the Federal Aviation Administration. The efforts of the UNIVAC personnel, particularly Mssrs. J. Flood, D. Connett and W. Reid are appreciated in the software design and for assistance in preparing this paper.

BASIC METERING AND SPACING FOR ARTS III

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BIOGRAPHY

John R. Talley is the Chief of the Systems Design Section of the ATC Systems Division in SRDS. He attended Pennsylvania State University majoring in chemistry. He has been both a terminal and en route Air Traffic Controller and has been involved in many automation program developmental activities of the FAA. He has programmed the UNIVAC File Computer, 1218, 1219 and the IBM 1410, 7090, 9020. While in National Airspace System Program Office (NASPO), he led on the testing and integration of the ARTS III systems and has been in his present position since 1972.

ABSTRACT

This paper provides a detailed description of the computer program being developed to add a Metering and Spacing (M&S) function to the ARTS III system in use at over 60 major U.S. airports. An experimental version of the M&S program has been integrated with the ARTS III system and currently is under test and evaluation at the National Aviation Facilities Experimental Center (NAFEC) at Atlantic City, N.J. This paper concentrates on the control functions, and how they are generated and does not address the changes required to the tracker, the interface with the ARTCC nor the data entry additions to the ARTS III operational program.

BACKGROUND

The study of M&S concepts dates back to the late "50's" and in the early "60's" a significant amount of simulation activity was performed by the FAA and by MITRE Corp. These efforts led to two field test programs: FASA (Final Approach Spacing for ARTS) and CAAS (Computer Aided Approach Spacing) which were developed in the mid "60's".

FASA was designed by FAA NAFEC for integration into the ARTS I system in Atlanta, Ga. UNIVAC developed the software, and the FAA conducted the evaluation. Because of a variety of problems, including procedural incompatibility and increased controller workload, the evaluation was suspended and few conclusive results were obtained.

CAAS was developed by the FAA for testing at New York's JFK airport. Like FASA, CAAS suffered from various inadequacies (primary was the lack of a tracker) and also, failed to provide conclusive results. However, these early systems did show that an M&S function could provide more consistent and accurate landing intervals.

After the ARTS III system was under development, the FAA prepared a comprehensive specification for an M&S function for ARTS III. The requirement called for studies, simulation, design development, and testing at NAFEC and at a field site. The contract was awarded to Computer Systems Engineering (CSE) Corp. in early 1970. After nearly four years, CSE had not successfully completed development of the basic M&S function. The government terminated the contract and, in the fall of 1974, awarded the M&S ARTS III contract to UNIVAC on a sole source basis. This contract called for an analysis of the CSE end items and the development of an M&S function suitable for field evaluation.

That system is now available at NAFEC. The system is operating with an ARTS III operational program with conflict alert and is currently undergoing test and evaluation. Previous systems, under other versions of the ARTS III operational program were also successfully tested, including compilation of performance measures. This system marks the first time that the FAA has possessed an M&S program where testing is repeatable and performance can be measured.

FUNCTIONAL DESCRIPTION

The Metering and Spacing function has been developed for integration into an ARTS III, single beacon system. The specific software

has been designed to be integrated into the Denver Configuration of the ARTS III operational program, for use in test and evaluation at the National Aviation Facilities Experimental Center (NAFEC).

The hardware configuration is shown in Figure 1.

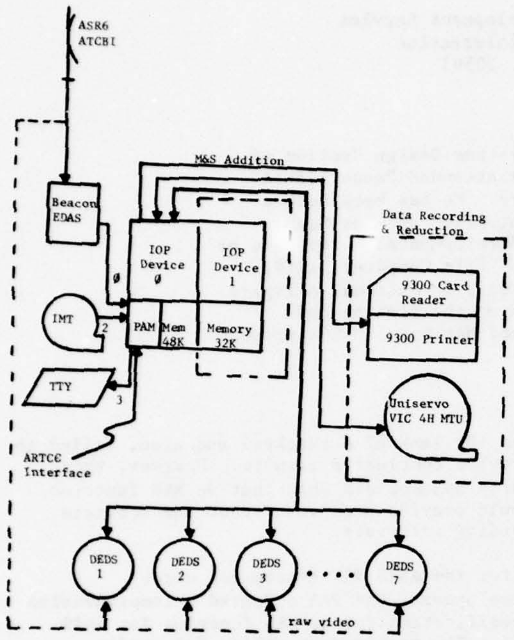

FIGURE 1, ARTS III, M&S EQUIPMENT CONFIGURATION

The M&S system is intended to aid in the control of arrival aircraft, scheduling and spacing those aircraft for minimum delay landings. The design provides flexibility for adapting the M&S to any ARTS facility although only the Denver environment was analyzed to verify that the design flexibility was adequate. The M&S design also provides for incorporation of different runway configurations, i.e., provision to reconfigure the system for an alternate approach. Four configurations for Denver's Stapleton International Airport have been developed for testing at NAFEC:

1. Trombone Approach to Runway 26L

2. Transition, Approach and Local Landing Approach to Runway 26L

3. Profile Descent Approach to Runway 26L

4. Profile Descent Approach to Runway 17R

The M&S design does not include provision for multiple airports or for multiple runway operations at the same airport. Provision for departures are made through use of normal gaps in the arrival stream as well as through data entry requests.

The primary objective of M&S is to enable an increase in airport capacity without adversely impacting system safety. The increase in system capacity will be achieved by providing more consistent inter-arrival spacing of aircraft, thus assuring an increase in runway utilization. The automated M&S function may also prove beneficial in other areas such as an overall reduction in arrival delays, the equitable distribution of delays, and the absorption of any necessary delays in the most efficient manner.

Safety shall be maintained by assuring that recommended control actions are within the bounds of aircraft performance characteristics, and by assuring that control is in accordance with existing ATC procedures and practices.

In general, the M&S function will: a) control the flow of arrival aircraft into the terminal area, termed Metering: b) determine the landing order based on each aircraft's nominal landing time, using predefined flight paths, termed Sequencing, and c) establish schedule times at various points for each aircraft which will assure proper spacing of aircraft at and inside the final approach course intercept. The M&S then aids in the control of arrival aircraft by the generation of recommended commands to satisfy the established shcedules.

The M&S system may be divided into nine major functions as listed below:

1. Executive Control
2. Command Generation
3. Scheduling
4. Metering
5. Display Output
6. Keyboard Input
7. ARTS Tracking Improvements
8. Adaptive Wind
9. Data Recording and Reduction

Executive Control - The Executive Control Function is essentially identical to the basic ARTS dual beacon system and provides for control of all other functions on a priority basis in addition to power failure recovery logic.

Command Generation - The command generation module provides four different approach geometries, representing three unique control concepts. The first is a "trombone" approach to runway 26L in which a fixed (downwind) heading from the inner fix (IF) is generated. The second is a TALL (Transition, Approach and Local Landing) approach to 26L which provides a variable (fan) downwind heading from the IF to absorb all delay. The third and fourth geometries provide for profile descents to runway 26L and 17R, respectively. The profile descent (PROD) geometries use a restructured arrival airspace and provide fixed downwind

heading from two IF's and fan type headings from the other (remote) IF's. (See Figure 2) PROD geometries also inhibit the display of sequence area headings (performed by the pilot in accordance with published procedures). In other respects the geometries are comparable, i.e., *in each* geometry M&S determines a sequence, calculates the delay, if any, and provides the necessary commands to satisfy the established schedules. M&S also performs resequences, when the existing sequence is undesirable or unattainable, and issues altitude and speed commands to conform with the desired approach pattern.

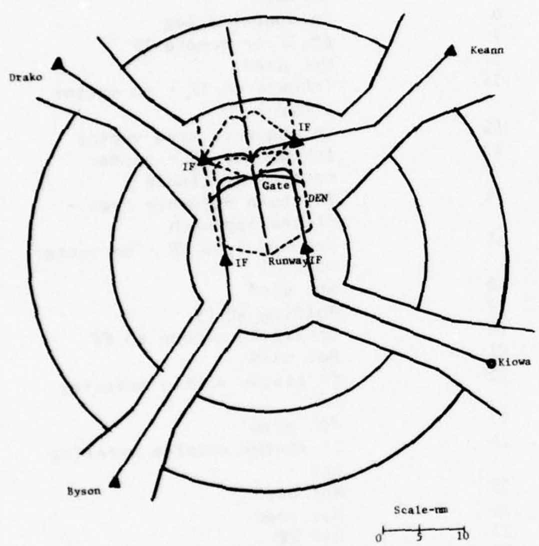

FIGURE 2, PROD APPROACH GEOMETRY TO 17R

Aircraft are automatically placed under M&S control when *Flight Plan (FP)* data is received which indicates that the aircraft is an arrival to the M&S controlled airport. FP data may be received from the En Route Air Traffic Control Center or via manual keyboard entry.

Command Generation requires four unique pieces of information. These are:

1. The predefined approach geometry.
2. The aircraft profile data (aircraft characteristics).
3. The aircraft performance measurements.
4. The aircraft schedules.

The approach geometry consists of prestored information (the Geometry File) which specifies all M&S control points and identifies the various approach paths. A unique Geometry File is required for each configuration. The Geometry File approach paths are dependent upon the aircraft performance class and the Feeder Fix (FF).

Two performance classes are defined for M&S: a high performance class for all aircraft capable of maintaining 180 knots indicated *airspeed*; and a low performance class for all other aircraft. The performance class is predefined, and based on *the* aircraft type (contained in the flight plan data).

Arrivals use one of four approach gates. Each gate may have one or more feeder fixes. The FP data may identify any one of these fixes for simplicity. The M&S defines "logical feeder fixes," each of which (up to 31) will be dedicated to either high or low performance aircraft. Each assigned fix shall have an associated logical feeder fix and each logical feeder fix has an associated set of data defining the unique approach path from that fix.

The approach path *for each* FF are divided into four segments (Figure 3)

1. The transition area
2. The sequence area
3. The base area
4. The final area

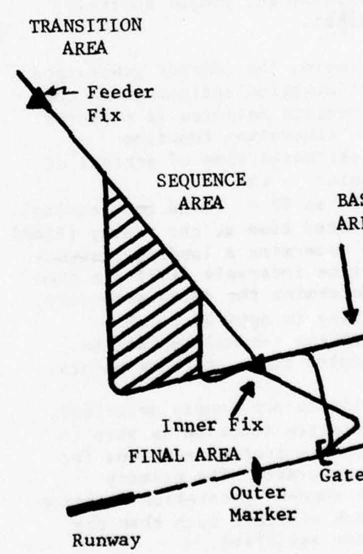

FIGURE 3, SEGMENTS OF THE APPROACH PATTERN

Areas of controllability are normally provided in both the sequence and base areas. Various methods are available to define the approach routes, i.e., control arcs (a distance from a referenced point), limit radials (measured from a referenced point), and/or prestored headings, may be used to specify the approach path.

Profile data is derived from the aircraft type and is used to determine the aircraft's probable speed, rate of descent, and rate of deceleration within each segment of the approach path.

Aircraft performance measures include identification of the current position, speed, heading and altitude, and a calculation of the anticipated time to fly, (TTF) to the next schedule point. The anticipated TTF is calculated by a Direct Course Error (DICE) program along both the minimum and maximum routes. Also, along both routes, two times are calculated: the first assumes a constant speed until slowdown (to the nominal) is required to satisfy the geometry data; and the second time assumes immediate slowdown to the nominal speed specified for the next schedule point. Thus, four different times to fly may be calculated:

1. TTFA: Minimum path with final slowdown.
2. TTFB: Minimum path with initial slowdown.
3. TTFC: Maximum path with final slowdown.
4. TTFD: Maximum path with initial slowdown.

The two extremes (TTFA and TTFD) represent the total controllability available between the aircraft's position and the next schedule point. All of the calculated times to fly, together with the schedule time at the next point, are used by the command generation function to determine the proper control actions to be taken.

Schedule data provide the command generation function that information against which the aircraft's performance measures is compared. Very simply, the scheduling function calculates the estimated time of arrival at each schedule point -- the runway, gate, IF, an FF -- based on a nominal path. The estimated time at the runway (ETAR) is then used to determine a landing sequence. Proper landing time intervals (LTI) are then calculated to determine the delay necessary. Finally, that delay is applied to the estimated time at the schedule points to define the scheduled times at those points.

Using the four inputs previously described, the command generation function is able to determine appropriate control acctions for each of the M&S aircraft. The primary objective of the command generation function is to control each aircraft such that the schedule times are satisfied.

The techniques used to perform the control task, the decisions regarding the generation of commands and the degree schedule adjustment attempted are dependent upon several factors including the aircraft's location in the approach path and the approach path characteristics. The command generation function therefore employs unique decision making logic for each segment of flight within the approach path. For control purposes, each aircraft is assigned a "status" which reflects the aircraft's position within the approach path.

As each aircraft enters the ARTS-M&S system and proceeds toward the runway, the status associated with that aircraft is adjusted to reflect the position within the approach path and to dictate the control decisions necessary. The various statuses are listed in Table I.

Table I M&S Status Assignments

Status Number	Description
0	No M&S control
1	Not used
2	On final
3	Heading to gate or on ILS intercept
4	Not used
5	On base
6	On downwind leg
7	At IF or remote IF
10	Not used
11	Inbound to IF - no vector control
12	On sequence area vector
13	Inbound to IF - vector control available
14	Two turn Sequence Area - Missed Approach
15	Inbound from FF - no vector control
16	Not used
17	Holding at FF
20	Active & inbound to FF
21	Not used
22	FP status within metering arc
23	Not used
24	FP status outside metering arc
25	Not used
26	Not used
27	New FP
30	Not used
31	Not used
32	Not used
33	Not used
34*	On Final Approach Intercept
35*	On base
36*	On downwind
37*	At IF

* Used for TALL geometry

In general, within each status, command generation logic follows a consistent set of objectives. These objectives are as follows:

1. When the calculated aircraft performance measures indicate that the aircraft can arrive early at the next schedule point, an attempt is made to adjust the schedule (slip forward).

2. When the calculated aircraft performance measures indicate that the aircraft will be late at the next schedule point the command

generation function shall effect a schedule adjustment (slip backward).

3. Command generation shall attempt to maintain the current speed and altitude until a deceleration or descent command is required to assure that the nominal speed for altitude is satisfied.

4. An early speed reduction shall be issued when:

a. the aircraft will be early (minimum path with final slowdown), and
b. the attempt to slip forward was unsuccessful, and
c. the aircraft is flying directly to the schedule point, and
d. the slowdown is adequate (without a delay vector) to satisfy the scheduled time.

5. When the aircraft is early and flying directly to the next schedule point, and a speed reduction will not satisfy schedule requirements, a delay vector (prestored heading) shall be issued if permitted by the approach path. Issuance of the heading command shall be delayed until the maximum path with final slowdown, will satisfy the schedule time, i.e., commitment to a delay vector is postponed in anticipation of a forward slip to preceding aircraft, precluding the necessity of a path stretching delay.

6. When an aircraft is flying indirectly to the next schedule point, the maximum path is used in preference to earlier speed reductions, much as a delay vector described in 5) above.

7. Altitude descent commands are generated such that the aircraft will attain the desired altitude at the control point based on TTF calculations. Initiation of the descent command considers the current speed and the descent rate.

Note that the accuracy of delivering aircraft to a schedule point will be dependent upon the specific point, i.e., command generation will attempt to deliver aircraft to the IF within 20 (parameter) seconds of the schedule times but additional accuracy will be used for delivery of aircraft to the gate. Where it is found that the desired accuracy cannot be attained, schedule adjustments will be attempted. Schedule adjustments (slip forward or back) will be common in the sequence area since inaccuracies can normally be handled by using base area controllability.

Two methods of speed control were considered in the design. The two methods were "fixed point-variable speed" and "variable point-fixed speed." The latter is used in the M&S program, primary because of its commonality with current ATC practices, although logic is provided to adjust the "fixed" speed when aircraft capabilities (profile data) dictated.

The M&S program provides two levels of FF control. The first level of control is performed by the metering function. After the schedules based on FP data have stabilized, the metering function will generate a proposed time of departure from the FF for each M&S controlled aircraft which requires delay of more than three minutes (a path dependent parameter).

The second level of FF control is provided by the command generation function when the aircraft is two minutes (parameter) from the FF. If not available, an updated ETA from the ARTCC is used. If no updated ETA is available, the initial ETA is assumed to be accurate.

When the aircraft is determined to be within two minutes from the FF, the command generation function will examine the schedule relative to the ETA. A recommended hold shall be generated if:

1. The delay to be asborbed exceeds some portion (y) of the available controllability (where (y) is a path dependent parameter),

2. Holding is permitted at the assignment logical FF,

3. The scheduled delay exceeds three minutes, or if,

4. The preceding aircraft through that logical FF was scheduled to hold and is not schedule to depart that fix before one minute prior to this aircraft's estimated time of arrival at the FF.

The Command Generation function shall control all scheduling operations. Gross scheduling of all Denver arrivals shall be performed when the Flight Data is first received. That schedule data will be used to perform the metering function and to determine FF holding requirements. Rescheduling will be requested when any new data is received, e.g., FP updates pertaining to ETA or aircraft type, or track activiation, which permit computation of ETA. Command generation then requests Tentative scheduling when each aircraft has penetrated the FF and is inbound to the IF. Thereafter, only schedule deletion, or adjustments are requested. No "firm" scheduling is required.

Scheduling

The objective of the scheduling function is to determine an acceptable landing sequence and, based on that sequence, to determine schedule times at various points within the approach path. The schedule points are the runway, gate, inner fix, and feeder fix.

Scheduling is performed in support of the command generation function, i.e., command generation, based on aircraft performance, will request the establishment of schedules, schedule adjustments, and rescheduling. Like the command generation function, scheduling requires the geometry information, profile data and aircraft performance measures. Normally, the aircraft performance measure will be anticipated values based on the profile and geometry data.

The scheduling function is divided into seven tasks.

1. Schedule Activation
2. Gross Scheduling
3. Tentative Scheduling
4. Rescheduling
5. Schedule Adjustment
6. Resequencing
7. Schedule Deletion

Schedule activation occurs when data are received indicating an arrival to the airport. That information is normally received via flight plan data from the En Route Center. It may also be received via data entry. The schedule activation task establishes a new M&S file and then calls on a scheduling task to establish schedule data.

The objective of gross scheduling is to determine the landing sequence and, based on that sequence, to determine estimated times at various schedule points and the delay which must be absorbed. The gross scheduling data is used by the metering function to determine a proposed time of departure from the FF for transfer to the En Route Center.

Generation of a gross schedule consists of first calculating an estimated time of arrival at the runway (ETAR). This requires calculating the time to fly (TTF), the sequence, base and final areas. Those times, together with the FP indicated ETA are used to determine the ETA at the runway (ETAR). The TTF calculations use the aircraft performance measurements which include both minimum and maximum times to fly. The times used for scheduling are the minimum times to fly (TTFm) plus a constant (the constant is an approach path dependent parameter which compensates for computational errors and/or the "desired" arrival path as opposed to "minimum" path).

Calculations regarding the TTF the sequence area (TTFs) is perhaps the most unpredictable segment since current ATC practices differ widely and are dependent upon load. Thus, if the aircraft is in active status (tracking), actual track speed shall also be considered, i.e., the lower of nominal or actual will be used.

The calculated ETAR is then merged with the ETAR's of all other scheduled aircraft. The merging process (an ordering by time) defines the gross landing sequence, i.e., "first-come-first-served at runway" criterion is used to define the arrival sequence.

After the landing sequence is established, a landing time interval (LTI) between the new aircraft (n) and the preceding aircraft (p) is computed. LTI is used to assure that sufficient separation is maintained between each pair of aircraft on final.

LTI is determined by computing four intervals, the larger of which is used as the LTI. The four intervals are:

1. A minimum interval at the gate, when the velocity of aircraft p exceeds n.
2. A minimum interval at the runway, when the velocity of aircraft n exceeds p.
3. A minimum interval based on the runway occupancy time of aircraft p (profile data).
4. A minimum interval based on a keyboard entered gap request.

Computations 1 and 2 above consider the small/large/heavy class aircraft in addition to the keyboard entered minimum separation criteria, i.e., the LTI shall be the greater of the separation required to satisfy the runway occupancy time, the keyboard entered gap requested, the keyboard entered minimum separation, or the minimum separation determined from the separation matrix shown below.

SEPARATION Minima (nm)

Leading aircraft:	Small	Large	Heavy
Trailing aircraft:			
Small	3	4	6
Large	3	3	5
Heavy	3	3	4

where aircraft classes are:

Small	12,500 lbs. or less
Large	12,500 - 300,000 lbs.
Heavy	300,000 lbs. or more

The LTI computation must provide for separation at the gate in cases where a slower aircraft is sequenced behind a faster aircraft. In this case, it may be assumed that (when the classes of aircraft are different) the high performance gate is outside of, or co-located with, the low performance gate, and the LTI shall be based on separation at the preceding aircraft's gate.

After the LTI is computed, the scheduled time at the runway (STAR), and the anticipated delay (if any) is calculated.

If the scheduled aircraft was not inserted into the gross sequence as the last aircraft, schedules of the following aircraft must be adjusted, i.e., a new LTI for n/n+1 is computed and the delay for n+1 (if any) is redefined in order to established a new proposed time of departure at the feeder fix for aircraft n+1. If a change in delay

results, the increased delay is then applied to all subsquent aircraft (if any) until sufficient slack is found to absorb the added delay.

Figure 4 depicts the relationships of values to establish the Landing Time Interval (LTI).

Tentative scheduling is performed when each M&S aircraft is inbound from the FF. This is detected by the command generation function. Generally, the objectives of Tentative and Gross scheduling are identical; however, there are several significant differences since gross schedules are already established, the holding capability has been lost, and more precise data will be required by command generation.

Tentative scheduling must adjust the scheduled data based on the time out of the FF. Tentative scheduling must also adjust the landing sequence, where desirable, to incorporate approach path priorities, and identify exact schedule times at the IF and gate, for subsequent use by command generation.

Tentative scheduling first computes the minimum and maximum times to fly the sequence area (TTFsm and TTFsx) and establishes a new ETA at the Inner Fix. Using the TTFb and TTFf from gross scheduling, a new ETAR may be defined. Two options exist: 1) the new ETAR could be used to determine a new sequence, or 2) the initial sequence could be used to determine a new value of delay. The second approach preserves the first come sequence (to the extent possible) even where there exists significant differences between the proposed time to depart the FF and the actual time through the FF. The first approach would effect a priority relative to the time through the FF and permits a smoother arrival flow. A combination of these approaches, wherein a new sequence is assigned only when the current sequence cannot be attained even using the maximum times to fly, is incorporated into the design.

After the new delay has been defined, that delay is allocated to the sequence and base area.

Schedule adjustments consist of a forward or backward schedule slippage. These are requested by the command generation function when current aircraft performance measures indicate the aircraft will be early at the next schedule point, or when the aircraft will be late, by more than n seconds (parameter, based on the aircraft status), even when taking the minimum path.

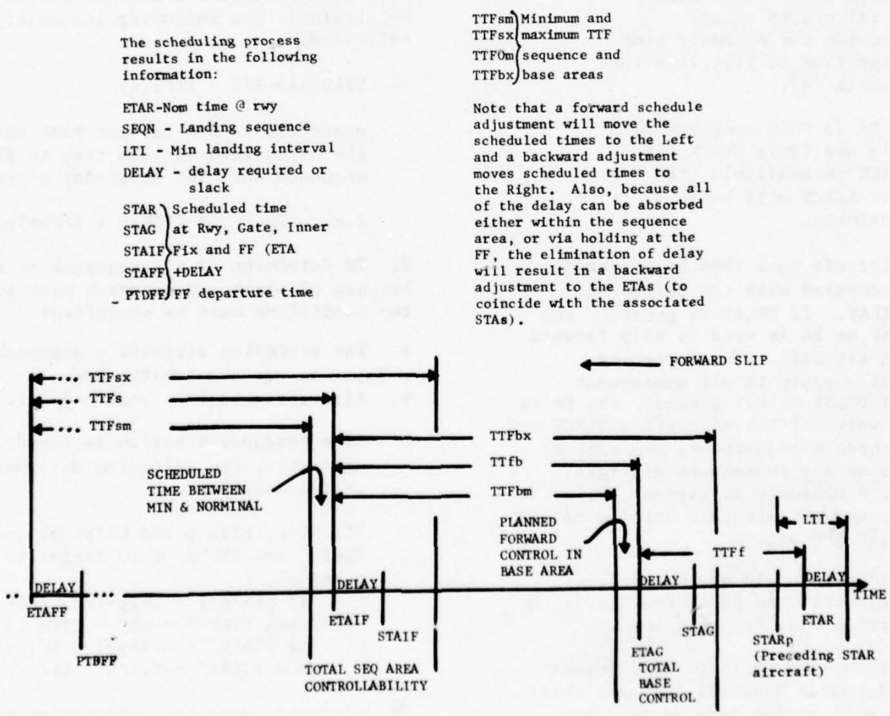

FIGURE 4, SCHEDULING DATA

Three different conditions may be detected by the performance measures when the schedule time (STA) is compared with the minimum and maximum TTF.

Condition 1 TTFm STA TTFx

Condition 2 STA TTFm TTFx

Condition 3 TTFm TTFx STA

Condition one indicates the scheduled time is attainable and no schedule adjustment is required. If the difference between TTFm and STA exceeds some value, a slip forward may be attempted.

Condition two indicates that the aircraft is late and a backward schedule slippage is necessary.

Condition three indicates that the aircraft is early and a forward slip will be attempted if the difference between TTFm and STA exceeds the parameter (the same parameter as used in condition one).

A forward schedule slip is attempted when aircraft performance measures indicate that the aircraft is early at the next schedule point (early by more than n seconds where n is a parameter dependent upon the aircraft status). The amount of schedule adjustment attempted is calculated as the difference between the schedule time and the minimum time to fly, less the accuracy criteria (n).

The value of FA is then compared with the aircraft's available SLACK (if any). If SLACK is available, the lower of FA or SLACK will be used for schedule adjustment.

Subsequent aircraft must then be adjusted, i.e., FA is compared with the following aircraft's DELAY. If DELAY is present, the lower of DELAY or FA is used to slip forward the following aircraft. The foregoing adjustments also apply to all subsequent aircraft. If DELAY is not present, the FA is added to the value of the aircraft's SLACK and no further schedule adjustments are made to that aircraft or any subsequent aircraft. Thus, a forward schedule adjustment will affect all subsequent aircraft until a natural gap is found in the sequence.

If the forward slip could not be performed because the aircraft had DELAY (no SLACK), a resequence action will be considered.

A backward schedule slip is performed when aircraft performance measures indicate that the aircraft will arrive late at the next schedule point (by more than n seconds, where n is a status-dependent parameter). The amount of backward schedule adjustment (BA) is calculated as the amount of late time.

The value of BA is then used to adjust all schedules for this aircraft.

Note that these adjustments are identical to a forward slip but, for a back adjustment, BA is a negative value. Again, as in a forward slip, the adjustment must be applied to all subsequent aircraft until sufficient SLACK is found to exhaust the value of BA.

The backward slippage to a following aircraft will result in an early condition for that aircraft. When that track is processed, a forward slip may be attempted. It would fail, however, since no slack is available and a resequence action would then be considered.

The automatic resequence capability is provided to adjust the landing sequence when:

a. The first-come-first-served criterion is undesirable because of differences in approach paths (approach paths may be assigned priority), or

b. Errors in the predicted aircraft performance resulted in a schedule which cannot be attained.

To determine when a resequence is desirable, the following criteria are applied.

1. To determine if a schedule resequence is desirable because the current schedule cannot be attained, the following inequality must be satisfied:

STAG(n) > RTC + TTFx(n)

where RTC is the current time and TTFx is the calculated maximum time to fly the sequence and base areas for aircraft n.

i.e., TTFx(n) = (TTFsx + TTFbx)n.

2. To determine if a resequence is desirable because of prestored approach path priorities, two conditions must be satisfied:

a. The preceding aircraft's approach path has a lower or equal priority, and

b. Aircraft n must be status $\geq$ 11.

If a resequence action is found to be desirable, the following data must be calculated:

LTIp-1/n, LTIn/p and LTIp/n+1 (new LTIs)
STARn' and STARp' (new tentative STARs for n and p)
If STARp-1 + LTIp-1/n > RTC+ TTFm(n)
then STARn' = RTC + TTFm (n);
or STARn' = STARp-1 + LTIp-1/n
and STARp' = STARn + LTIn/p

To determine, with the information now provided, if a scheduled resequence is to be accepted, one or more of the following

conditions must be satisfied:

1. The status of p is ≥ 17 (i.e., at or outside the FF), or
2. STARp' = RTC + TTFx(p)

A priority resequence is determined with the information now available.

To effect the new sequence, all LTI's and STA's for n & p must be restored and a new value of delay must be computed for all subsequent aircraft in the sequence (if any). That delay adjustment is applied to following aircraft in the same manner as a schedule slip.

Note that only a forward resequence is attempted, i.e., aircraft n ahead of p, where n is the aircraft in process. This restriction is imposed to assure that aircraft will continue to be processed in their scheduled order.

Note also that, while the scheduling algorithm attempts to effect and preserve a first-come-first-served sequence, the resequence algorithm adjusts that sequence in accordance with pre-established approach path priorities and current aircraft performance measures, relative to the schedules.

The maximum benefits of a "type-influenced" sequence depends upon the traffic mix and the ability to adjust the first-come sequence. For example, if a mix of Heavy/Large/Small was 30/50/20 percent, a random arrival sequence (first-come) would produce an average separation of approximately 3.8 nm, while the optimum separation is approximately 3.3 nm or an improvement of about 13%. However, since actual landing times cannot be adjusted to satisfy an optimum sequence, the actual improvement is expected to be less than 3%. Table 2 shows the random, optimum and achievable sequence of 20 aircraft, together with the resultant separation and percent of improvement.

TABLE 2

POTENTIAL SEQUENCE

(30/50/20 Mix)

RANDOM		ATTAINED		OPTIMUM	
TYPE/SEP		TYPE/SEP		TYPE/SEP	
L		L		S	
L	3	L	3	S	3
H	3	H	3	S	3
S	6	S	6	S	3
L	3	L	3	L	3
H	3	H	3	L	3
H	4	H	4	L	3
L	5	L	5	L	3
S	4	L*	3	L	3
L	3	S*	4	L	3
H	3	H	3	L	3
L	5	H*	4	L	3
H	3	L*	5	L	3
L	5	L	3	L	3
L	3	L	3	H	3
S	4	S	4	H	4
H	3	H	3	H	4
L	5	L	5	H	4
S	4	L*	3	H	4
L	3	S*	3	H	4
Total	72		70		62
AV SEP	3.78		3.68		3.26
% Improved	0		2.6 %		13.8 %

*Sequence changed

The attained sequence was obtained via an algorithm which considered each three aircraft in sequence and, when controllabilities permitted, interchanged the order to group similar aircraft types. The logic includes checks to assure that neither FF priorities nor aircraft controllabilities are violated.

The operational consideration is perhaps the most significant. Improvements can only be realized when system load is high. But to achieve improvements the sequence will appear abnormal (when compared to current ATC practices). The abnormal sequence will tend to increase controller workload (since system intent will be obscure) and, under heavy loads any increases in workload or any enigmatic system performance must be judged inappropriate. Therefore, incorporation of a type-influenced sequencing capability is not included in the M&S design.

An example of the resequencing mechanism follows. Assume that LFF1 has an assigned priority of 0.3 and that all other LFF's have an assigned priority of 0.9. Assume further that at time (RTC) 1500, aircraft C has just been tentatively scheduled, producing the following partial sequence. (For purposes of simplicity, a 100 second LTI is used for all aircraft pairs).

SEQ	TRK	LFF	ETAR	STAR	TTFsm	TTFsx	TTFbm	TTFbx	TFF
:									
16	A	3	2080	2200	200	420	180	420	200
17	B	2	2160	2300	280	580	180	600	200
18	C	1	2260	2400	440	590	120	150	200
19	D	2	2520	2520	640	890	180	600	200
:									

The desire for a resequence is satisfied because C's priority is greater than B's and because C's status is ≥ 11. The following test sequence is then established:

17	C	1	2260	2300	440	590	120	150	200
18	B	2	2160	2400	280	580	180	600	200

The resequence will then be accepted because:

$$STARp' \quad RTC \quad + TTFx + TTFm(1\ )$$
$$2400 < 1500 + .9(580 + 600 + 200) + .1(280 + 180 + 200)$$
$$2400 < 2808$$

Track C is then eligible for another resequence. The criteria to determine if the second resequence is desirable are:

$$STARn > RTC + \alpha TTFx + TTFm(1-\alpha)$$
$$2300 < 2314$$

Since the criteria do not indicate a desire for resequencing the second resequence will not be attempted.

A manual resequence may be requested via keyboard entry. In this case, one aircraft is specified, and that aircraft will interchange in sequence with the preceding aircraft. No resequence criteria used for the automatic resequence are applied. The new schedules for the identified aircraft and all affected subsequent aircraft are (re)established and, to assure that the manual action is not automatically reversed, the identified aircraft is flagged to inhibit any subsequent automatic resequence action. A manual resequence could result in unattainable schedules. This condition is indicated in the Alert Display when the aircraft is on the base leg, and prior to that, by large DICE values.

The schedule deletion is normally associated with the termination of M&S control for a specific aircraft. Schedule deletion is also performed whenever a rescheduling action requires that the current data be dropped and the new schedule inserted. In either case the task is the same; i.e., all schedule data will be erased from the sequence list and from the aircraft's data file. If the deletion is accompanied by a gap request, a gap will be provided (following the preceding aircraft), and no further schedule adjustments are required. If no gap is requested, the deletion action will effect a forward slip for all following aircraft. If any command is pending for the aircraft being dropped from the sequence, the command(s) will also be dropped. Note that this is the only condition in which a command can be automatically dropped.

METERING

Metering is defined as the process of adjusting the arrival flow to the airport acceptance rate. Many techniques are available to perform this function, including holding in the terminal area or at the handoff fixes, but in most instances, the most desirable technique is to perform the task of delaying aircraft in the En Route Center. The M&S program provides the capability to aid in this metering process, using the existing ARTS/En Route digital interface.

M&S metering is accomplished in two parts: First, M&S will automatically issue proposed FF departure times (PTD) to the ARTCC, for individual aircraft, based on anticipated traffic loads; and second, M&S will issue recommended Holds to the terminal controller, for individual aircraft, based on the anticipated delays required, and on the recommendations for preceding aircraft through the same FF.

The first part of metering attempts to eliminate holding at the FF by the absorbtion of delays within the en route airspace. The mechanism of holding aircraft at the feeder fixes is the final filter for a smooth metering of aircraft past the feeder fixes at the existing airport acceptance rate. The two parts of metering are described in the following paragraphs.

Flight plans for arrivals will be received by ARTS, from the ARTCC 20 (ARTCC parameter) minutes prior to the anticipated arrival of the aircraft at its feeder fix. Ten (approach path dependent parameter) minutes prior to the ETA, it is assumed that all flight plans for aircraft which could land ahead of this aircraft have been received. Accordingly, the schedule computed for this aircraft should be fairly accurate. At this time a PTD message will be automatically transmitted to ARTCC, if the scheduled PTD exceeds the ETA by more than three (parameter) minutes. The PTD may be used by the ARTCC controller to "burn-off" anticipated FF delays in enroute airspace.

In case the ARTCC controller is unable to eliminate a FF delay while aircraft is enroute, or if for some other reason the scheduling algorithm determines that the aircraft must hold at its feeder fix, then a proposed departure time for the aircraft will be displayed together with a hold indicator. The ARTS controller may then verbally notify the ARTCC controller of the need for holding the aircraft at the feeder fix, or, the ARTS controller may absorb the delay if the aircraft is under terminal control.

<u>Display Data</u> - The M&S Display Output function is integrated into the ARTS III operational program and will add seven categories of display output data:

1. Command Data
2. Sequence Data
3. FF Data
4. Wind Data
5. Parameter Data
6. Display of DICE
7. Separation Alert

M&S commands consist of recommended headings, speeds and altitudes for all M&S controlled aircraft. A single command for any aircraft may consist of one or more of these components, e.g., Heading, Altitude and Speed.

A heading component is presented as an L or R (left or Right) followed by three numerics (005-360) indicating the magnetic heading to the nearest five degree. An altitude component is presented as an A followed by three numerics indicating a "procedural" assigned altitude in hunderds of feet. A speed component is presented as an S followed by three numerics representing indicated airspeed, rounded to the nearest ten knots.

Command data is presented in the third line of the aircraft's Full Data Block (FDB) format. When more than one component is presented, all shall be contained in line three with a presentation priority, from the left, of: Heading, Altitude and Speed. Commands are presented at the controller's display and, like ARTS FDB data, the commands may be viewed at other displays only when that track is in handoff to, just accepted from, quick looked, or readout by another display.

The M&S provides for presentation of commands in one of two modes: a Multiple Command Mode (MCM) or a Single Command Mode(SCM). The mode is selectable by keyboard entry and pertains to all display. The alternative modes are provided for evaluation purposes but on-line mode change is permitted without loss of command information.

In the multiple command mode, all commands are presented to the controller ten seconds (parameter, 0-12) prior to the desired time of (aircraft) execution. The command component is presented forced and non-blinking for six seconds (parameter, 0-7), then changes to a forced, blinking format for four seconds (0-15), and then returned to the forced, non-blinking format for six seconds (0-7), before the presentation is automatically dropped. If a command is to be presented and the associated aircraft is presenting the same command component, the old component will be dropped and presentation of the new data is initiated. New commands of unlike components are simply added to the command line.

Sequence data consists of an M&S generated landing sequence number, the assigned runway, and the required separation, in nautical miles, between this and the preceding aircraft.

The landing sequence indicator shall be a single numeric presented in place of the FDB position symbol. Sequence numbers are assigned on a system basis, 1-9, then 0 for the first ten aircraft in sequence, then 1 for the first ten aircraft in sequence, then 1 for the eleventh, etc.

Runway assignment consists of two numerics or two numerics and an L or R (e.g., 08 or 26L), and is presented in place of the scratch pad data in field two of the FDB format. The runway is automatically assigned (based on the selected geometry - 26L or 17R) or manually modified via keyboard entry (F11, ID△, R or L Enter).

The minimum separation is a single number (1-9 nm), obtained from the LTI computation, i.e., the minima separation matrix or the keyboard requested gap or the automatically generated gap. If the separation is greater than nine, 9 is presented. The separation is presented in field three of the FDB format, replacing the asterisk, and is timeshared with the handoff indicator. The separation pertains to the interval between this and the preceding aircraft and is presented for all M&S aircraft.

Feeder fix data is provided for all M&S controlled aircraft outside of the FF and within two minutes (parameter) of the ETA at the FF. The data consists of a time, in minutes after the hour, at which the aircraft is to depart the FF and hold indicator (HOLD) implying M&S has recommended a Hold.

For all M&S aircraft scheduled to hold, the FF data blinks for ten seconds (parameter), one minute (parameter) prior to the scheduled FF departure time. FF data is presented two minutes prior to the anticipated aircraft arrival at the FF and is dropped when the aircraft is detected as inbound from the FF.

FF data is continuously updated except that, for aircraft in Hold, changes to FF departure times will not be made after one minute prior to the scheduled departure time.

A tabular readout of the M&S wind data is provided. The readout is available only at the supervisory position. The list is relocatable. The data presented indicates wind Heading and Speed for both averaged National Weather Service and Adapted winds in each of the twelve wind collection areas. The number of updates (up to six) which were used to attain the adapted data is also shown.

A tabular list of miscellaneous M&S information is provided. Like wind data, the presentation is available only at the supervisory position, and is relocatable. The list includes an updated count of M&S controlled aircraft, current geometry type, the separation criteria, the keyboard selected location of the high and low performance gates, and the runway occupancy times in seconds.

M&S provides the display of DICE in line zero of the FDB format. The DICE (Direct Course Error) is the Schedule time at the next schedule point (IF or Gate) less the computed minimum time to fly to that point, plus the current time. The DICE value consists of three characters (000-999) representing seconds. If DICE is negative (the aircraft is late), DICE is presented as two characters preceded by an N, e.g., N32.

The presentation of DICE may be inhibited (on a display basis) via keyboard entry. DICE is not presented at other displays via quick look, readout, etc. If MSAW data is active

for any aircraft , DICE data is inhibited until the MSAW presentation is terminated. The display of DICE is also inhibited during all M&S-anticipated turns.

M&S provides an automatic alert whenever it is determined that the predicted separation on final will be less than the computed minimum separation. This condition could result from a manually requested gap or resquence action which could not be accommodated within the M&S control capabilities, or it could result from M&S errors in predicting the aircraft performance. In any case, the presentation is the same. It is provided only for aircraft which have attained status five or lower (base leg) and it is presented in character positions four through seven of line zero. The presentation consists of one character (M or T), followed by the predicted separation. The character will indicate if the separation violation is predicted to occur at the intercept point (M), i.e., outer marker, or at touchdown (T), i.e., the runway. The predicted separation (at the point indicated) is presented in nautical miles and tenths of nautical miles. The alert message, like DICE, is overridden by an MSAW message and is not presented via quick look, handoff or readout actions.

SYSTEM PERFORMANCE

The preceding sections have presented a description of the M&S functional capabilities. Of interest now is the overall system performance which can be expected when these functions are implemented in an operational environment.

Anticipated system performance is dependent on an extensive list of variables, including the controller and pilot response times, the volume and mix of aircraft under M&S control and the relative load on the various feeder fixes, as well as the values selected for various parameters. Some of the performance parameters are:

1. Separation Criteria
2. Assigned Feeder Fix Priorities
3. Holding Criteria
4. Schedule Adjustment Criteria
5. Gate Locations.

While many of the factors affecting performance can be fixed, it still remains apparent that accurate performance measures can only be obtained through simulation. The M&S evaluation at NAFEC is performed in a simulation environment and data recording/reduction capabilities have been developed to provide the information necessary to measure system performance.

System performance can be measured in various ways. The aircraft's ability to satisfy the schedule times is one criterion; however, since schedules (within the M&S) are simply approximately estimates of arrival times which will be continuously updated and adjusted as new data becomes available, that critierion is not, by itself, adequate. A second and perhaps better measure of performance is the inter-arrival times attained under heavy load conditions as compared to the desired (calculated) interarrival times. For example, when two aircraft have been scheduled and the second (in sequence) is required to absorb some delay to satisfy the minimum landing time interval (measured at the gate), the accuracy in attaining that LTI is a satisfactory performance measure.

A third measure of performance can be obtained by measuring the amount of delay required for all aircraft in a sample and comparing the average delay to the range of delays encountered. If approach path priorities were not used, the range of actual delays should be normally distributed about the average with an acceptable deviation. If approach path priorities are used, the average and range of delays on each set of fixes having different priorities must be evaluated. When the various groups are compared, a measure of the success of FF priority scheduling will be revealed.

A fourth measure of performance can be obtained by comparing the percentage of holds (at the FF) with the arrival rate attained. Simulation activities performed during the System Evaluation phase have shown that if a maximum arrival rate of 40 aircraft per hour can be attained (dependent upon aircraft mix and separation criteria), an arrival rate of 32 could be attained with ten percent of the aircraft required to hold. As additional system loads are effected, holding requirements will increase and the arrival rate attained will approach 40. The simulation did not consider system errors in measuring aircraft performance. This would reduce the anticipated arrival rate attained with a ten percent hold factor. Arrivals (for simulation) were given a Poisson distribution, i.e., interarrival times were exponentially distributed.

Other performance measures will be required for evaluation of individual M&S functions, i.e., evaluation on a functional (or item) level, in addition to overall system performance. The functional evaluation includes measurements of the adaptive wind performance, display throughput (delay from event to presentation of that event), the volume of commands generated, the impact of resequencing on approach path priorities, the impact of metering information, and the improvements realized for tracking modifications. Each of the above areas will be evaluated to determine their impact on total system performance.

PERFORMANCE CRITERIA AND DESIGN GOALS

Once performance data is collected it must be evaluated according to some criteria e.g.,

what inter-arrival gap accuracy is required, what is a tolerable range of aircraft delays, what constitutes successful scheduling when priorities are assigned to various approach paths, and what arrival rate is acceptable when holding is required for one aircraft in ten? Item evaluation criteria is also required, e.g., what are acceptable errors in adaptive wind, tracking, etc?

The design goals for M&S are listed in Table 3. The design goals provide measurements in both an error-free environment and in a system which includes random system errors. The system errors to be provided are listed in Table 4. The system performance will be measured in a simulation environment, using the various traffic loads and traffic mix, e.g.,

Low Demand	10 - 20 aircraft/hour
Medium Demand	21 - 20 aircraft/hour
High Demand	31 - 40 aircraft/hour
Traffic Mix	0 - 10% low performance

TABLE 3 SYSTEM DESIGN GOALS

Performance Measure	Criteria (1 sigma) Error Free	System Errors
System Performance		
Inter-arrival Gap Accuracy	8 sec	11 sec
Arrival Rate (3 nm sep & min gate)	38/hr	35/hr
Item Performance		
Tracking - Straight Flight		
Heading Errors	5^{o}	8^{o}
Speed Errors	10 kts	10 kts
Metering Performance		
PTDFF Accuracy	± 2 min	± 2 min
Command Generation-Av/Aircraft	6.5	6.5
Adaptive Wind Accuracy		
Speed	15 kts	20 kts
Heading	15^{o}	15^{o}

TABLE 4 Simulation System Errors

Source	Error (2σ)
Data Acquisition (Target Simulator)	
Azimuth	0.25^{o}
Range	200 ft.
Target Declaration	95%
Wind Errors - Deviation from True	
Speed	20 knots
Heading	40^{o}
Aircraft Performance (Target Simulator)	
Heading - Navigation	1^{o}
Heading - Vectoring	4^{o}
Speed (commanded vs achieved IAS)	10 knots
Descent Rate	$\pm$ 10%
Deceleration Rate	$\pm$ 10 knots/min.
Turn Rate (IAS $>$ 210 knots)	1.5^{o}/sec. $\pm$ 0.25^{o}/sec.
Turn Rate (IAS $<$ 210 knots)	3^{o}/sec $\pm$ 0.5^{o} sec./
System	
Command Generation to Execution	6 sec. $\pm$ 4 sec.
FF Arrival & Departure Error	1 min.
Percent of Commands Executed	100%

SYSTEM EXPANSION

The preceding sections have addressed the requirements, capabilities and objectives of the basic M&S program, integrated with an ARTS operational program. The following is a short discussion of several potential enhancements which may be required for future operational implementation in a high density terminal environment, and to assure that those enhancements are consistent with the basic M&S design philosophy.

The conceptual requirements for expansion of M&S include on-line geometry selection, multiple runway operations and multiple airport operations. Both the functional capabilities and the implementation requirements are described. Potential enhancements to include departure control or full VFR/IFR arrival control are not considered herein.

On-line geometry selection generally implies a runway change a significant event in most terminal facilities. The basic M&S provides a keyboard entry to select the desired geometry; however, if a geometry change is made when aircraft are under M&S control, the active aircraft will be removed from M&S control. A more desirable approach is to retain control of all aircraft, to both runways.

To provide this level of capability, the runway selection entry must be expanded to identify the first aircraft which will utilize the new runway. The program would then reschedule the identified, and all subsequent aircraft, using the new geometry data. The preceding aircraft in sequence would be flagged to assure that: 1) following aircraft are not resequenced ahead, and 2) a special LTI is used between the identified and the preceding aircraft.

With this approach, the system must be capable of operation with two or more active geometries, and this necessitates some additional data base requirements. Two structures are feasible: The basic M&S uses several sets of geometry dependent tables, with each set providing an "active" table provides easy data access and permits a gate location change to affect only the current data. This approach can be expanded such that each table within a set includes an active table; however, this represents a significant increase in memory, only to preserve original geometry data in the event of a gate change. Instead, it appears desirable to eliminate the existing "active" tables and allow the appropriate data to be accessed directly, using a geometry index associated with each aircraft. The geometry index would be stored upon scheduling of each aircraft, and used to obtain any geometry-dependent data. Gate location changes would not be allowed. If alternate gates are desired, they could be stored as different geometries.

In summary, provision for on-line geometry changes would require:

1. An expanded entry to identify the first aircraft to use the new geometry.
2. Logic to flag the identified and all subsequent aircraft for rescheduling and to flag the preceding aircraft for special LTI and resequence considerations.
3. Logic to assign the proper (new) geometry for any missed approach to the old runway.
4. Retention of a geometry index in association with each aircraft, and use of that index in referencing all geometry-dependent tables.
5. Deletion of all "active" tables and deletion of the gate change capability.
6. Addition of alternate gate locations as new geometries.

Of these, the only significant change is the use of a geometry index for referencing the geometry-dependent tables. However, since the gate change capability must be provided, that index cannot be used in the basic.

In concept, multiple runway operations may be divided into two categories: dependent (or interfering) runways and independent (non-interferring) runways. Independent runways will be treated in the same manner as a multiple airport operation. Dependent runways, however, can be provided within the basic M&S design framework, i.e., all aircraft will be scheduled in the same sequence and a schedule adjustment to one aircraft will affect the following (sequential) aircraft, regardless of the assigned runway. The significant differences in requirements to provide for multiple-dependent runways are logic packages to:

- Provide runway assignment, and
- Calculate LTI's when different runways are assigned.

Multiple airports, and independent multiple runways, may be provided using essentially a separate data base for each airport. The Control Track Table (CTT) however, need not be duplicated. Instead, the CTT is simply expanded to provide adequate files for all arrival aircraft. Each file will indicate the aircraft via the geometry index. A separate sequence thread is then maintained for each airport, i.e., one "first in sequence" is identified for each independent operation. The controlled aircraft are then processed as in the basic M&S (in their sequential order) but, after all have been processed for one airport, the next thread is initiated. With this approach few tables will be duplicated for independent operations since most data is already geometry-dependent and other data may be system dependent, e.g., wind data and profile tables may be system dependent. Changes will be required to identify the various airports in the enable and disable modes of M&S and in the modification of parameter data (runway occupancy times,

minimum separation, etc.). Several currently local parameters will also be expanded to geometry-dependent tables for greater flexibility in a multiple airport operation.

The most significant area of change is again the addition and use of the geometry index, and provision for that indexing is not provided in the basic M&S, since significant memory is necessary and since a gate change capability is needed in the basic M&S.

SUMMARY

The M&S program is currently under test at NAFEC with the interim results indicating that the design goals are achievable. In mid-1978 the M&S program will undergo extensive testing with the Automated Conflict Alert function where the emphasis will be placed not only on quantifying the M&S performance but also on demonstrating the compatibility of M&S and Conflict Alert.

The quantified performance data and the results of the NAFEC evaluation will be used as the basis for a decision to conduct a field evaluation of the metering and spacing function at a busy airport. This is judged to be a prerequisite to the next phase of development which would lead to system-wide implementation.

ACKNOWLEDGEMENT

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REFERENCE

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TERMINAL INFORMATION PROCESSING SYSTEM

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BIOGRAPHY

Nathan Aronson is the Acting Chief, System Analysis Section in the Terminal Branch, part of the Air Traffic Control Development Division. He received his BS in Electronic Engineering in 1957 from *Polytechnic Institute of New York* and his M.S. in Transportation in 1973 from the University of California, Berkeley. Mr. Aronson has contributed to the development of terminal automation programs. In addition, he served in the Office of Aviation Policy where he conducted economic analysis of major FAA development programs. Prior to coming to the FAA in 1959, Mr. Aronson was a radar design engineer in private industry for two years.

ABSTRACT

This paper presents a technical overview of the development program for the Terminal Information Processing System (TIPS). It describes some of the background milestones leading to the present SRDS development efforts. It also describes the extent of the current development activities and some future possibilities. It reviews the TIPS design objectives and describes the technical features.

PRODUCTS/EXPECTED RESULTS:

a. TIPS Program

The TIPS equipment is being designed and procured to provide an efficient electronic means to process and distribute flight data and other operational information which can be integrated into the National Airspace System. The TIPS equipment is intended to replace the Flight Data and Printout Equipment (FDEP) and associated paper flight strips.

The TIPS development program is intended to provide prototype model equipment that will demonstrate the validity of the design in so far as system integration with the National Airspace System, performance and man-machine compatibility. A final design based upon field tests will result in a hardware/software specification (technical data package) that will be turned over to the Operating Services for field implementation at ARTS IIIA locations.

TIPS procurement will involve the design, fabrication, test delivery and installation of two functional prototype model TIPS. One prototype system will be installed in the Terminal Automation Test Facility (TATF) at the National Aviation Experimental Center (NAFEC) and the other will be installed at an operational ARTS IIIA terminal facility. Program Milestones are:

Funding Approved	FY-1978
RFP Issued	April 1978
Industry Responses Received	June 1978
Contract Award (Estimated)	January 1979
NAFEC Tests Begin	January 1980
Field Test Begin	May 1980
Field Test Ends	October 1980
Technical Data Package (Completed)	December 1980

b. TIPS Enhancements

The current program is directed toward providing basic flight data handling capabilities for the high and medium activity terminal environments served by ARTS III systems. The longer term E&D plan is to develop functional enhancements for these higher activity facilities and define configurations for application at lower activity ARTS III facilities, ARTS II

facilities and non-radar towers. TIPS equipment is expected to help consolidate hardware, software and communications requirements where TIPS is interfaced with other systems, i.e., Aviation Weather and Aeronautical Data System (AWADS), National Automatic Data Interchange (NADIN) System, Airport Surface Traffic Contract (ASTC), Wake Vortex Avoidance System (WVAS), Automated Flight Service Stations, Discrete Address Beacon System (DABS) Data Link. The TIPS equipment will also integrate and serve as a central display device for other operational data at controller positions in the tower cab.

C. Benefits

The effects of TIPS are expected to be reduced controller coordination workload, more timely availability of essential information and greater flexibility in configuration of tower control positions. In a study, by the Office of Aviation Policy (Reference 1), it was projected that there would be a 12% increase in controller productivity by automating the flight data handling. Other benefits that can be expected from TIPS implementation are Flight Data Entry and Printout (FDEP) equipment removal, thereby reducing extensive maintenance requirements, and improvements in safety.

BACKGROUND

In August 1973, the Air Traffic Service requested that Systems Research and Development Service undertake a development program to replace the FDEP at terminal facilities with an improved method of transmitting, distributing and updating flight data. This request for developing an improved Terminal Information Processing System was initiated because of the inadequacies of the present FDEP system at high activity ARTS III facilities. The FDEP system has basic capacity limitations which affect the availability and timeliness of flight data, especially in the more active terminals. Being largely of a mechanical nature, the FDEP equipment is also the source of considerable maintenance problems. Subsequently, a program was initiated and a system conceived. A National Flight Data Handling Seminar was held at NAFEC in November 1974. Ideas and information relating to terminal flight data handling were exchanged among the participants; air traffic control operational personnel, maintenance support personnel and development oriented groups. From this seminar additional operational features were formulated. During the next year engineering requirements were developed. In 1975 fiscal restrictions caused a hold in program activities. Funds were reinstated in FY-1978 and the program was reactivated. Subsequently, the Engineering Requirements (Reference 2) were updated and sent to industry as a part of the TIPS competitive procurement process. The FAA is now in the process of evaluating industry responses to the TIPS Request for Proposals (RFP).

TECHNICAL DESCRIPTION

TIPS will include those functions currently performed by the Flight Data Entry and Printout (FDEP) subsystem. However, FDEP has operational and system design limitations that affect system capacity and controller workloads within the terminal area. TIPS is intended to remove these limitations and provide an improved terminal capability for entering, displaying, and distributing flight and other non-radar data.

A primary objective of TIPS is to improve the availability and timeliness of flight data presentations to TRACON and Tower controllers. Currently, flight data from FDEP is available only for Instrument Flight Rules (IFR) flights, and may be delayed due to the FDEP's low data communications speed (100 words per minute). In addition, the ARTS computer contains only abbreviated flight data on IFR flights. With TIPS, full flight plan data can be displayed on the TIPS displays for all IFR and Visual Flight Rules (VFR) flights as soon as the information is entered into the terminal computer data base.

A second objective of TIPS is to reduce the controller coordination workload. With FDEP, flight strips are marked and distributed by the TRACON and tower controllers. Also, voice coordination is routinely required between tower and TRACON at the time flight responsibility is transferred. With TIPS, a single computer entry action will suffice to transfer flight and control information between tower controllers or between the tower and TRACON, or between towers.

A third objective of TIPS is to support the increased demand for VFR flight services. At present, several controllers may request the same basic flight information from a VFR pilot. With TIPS, this flight information can be initially entered into the terminal data base and thereby made available to all TRACON and tower controllers to assist them in providing VFR flight services.

The major operational capabilities provided by TIPS are:

a. Tower Electronic Tabular Display Presentations. Tabular displays are provided at the tower operational positions and will contain selected flight, weather and status information which is of current interest to the controller. The displays will also present full flight plan information in response to a controller request.

b. Improved TRACON Flight Data Presentations. The existing ARTS Plan Views Displays (PVDs) will be used to display summary flight data for all active flights (i.e., those which have a Full Data Block (FDB) displayed) and inactive

flights (i.e., those on the Arrival/Departure or Coast/Suspend List). Summary flight data is displayed by using the "alternate data switch" capability which causes flight data to temporarily replace tracking data on the PVD. In addition, summary flight data presentations for current and expected flights are presented on new tabular displays for planning purposes.

c. Enhanced Local Flight Data Entry. Local flight data will be entered into the computer data base for presentation on terminal displays. A controller will be able to enter VFR and local IFR flight plans, change IFR flights to VFR status, and make other flight data entries which relate to terminal area operations. Once the local flight data is entered into TIPS, it can be displayed at any TRACON or tower controller position which needs the information.

d. Improved Flight and Control Information Transfer. When control of a flight is transferred between the TRACON and a tower, a single controller action will usually provide the receiving position with sufficient flight information, thereby eliminating routine voice coordination. When a flight is transferred from one tower controller to another, a single controller action will replace the physical movement of the flight strip from one controller position to another.

e, Simplified Tower Manning Level Adjustment. In response to increases or decreases in flight activity, controller positions may be combined or decombined by a single supervisory action. When two positions are combined, the information displayed at those two positions will automatically be combined and presented on a single display. When a position is decombined, the information needed at the new position will be automatically presented on the new display, and the information needed at the original position will be retained on its display.

The TIPS design contains features that will increase the amount of data available to the controllers, reduce the time required to access data, provide system flexibility and expandability, and permit the use of low cost hardware for new functions, while limiting the impact on existing computer systems. The major design features are:

f. Centralized Terminal Flight Data Base. Flight data for flights of concern to a TRACON or tower controller are located in a centralized terminal data base and can be displayed almost immediately after it is requested by a controller. The flight data available to TRACON and tower controllers is identical.

g. Separate Processing System. Most TIPS processing, including the maintenance of the centralized terminal flight data base, will be performed in a new, separate processing system. The system will interface with the host ARTCC and collocated ARTS computers. Selection of this system design minimizes the changes required to the existing terminal software.

h. Mimimum Impact on Existing ARTCC Software. The messages currently sent by the ARTCC software to the FDEP (including full flight plans) will be sent to TIPs, and the message types received from the FDEP will be received via TIPS. The basic flight plan data currently sent by the ARTCC to ARTS will not be required, since it is a part of the full flight plan data which will be sent to TIPS. No other significant changes are required to the ARTCC software because of TIPS. The TIPS configuration will utilize the existing ARTS-NAS communication line. With an implemented TIPS, all FDEP-NAS lines may be deleted.

i. Moderate Impact on Existing ARTS Software. Presentation of flight data to Radar Controllers (using the alternate data switch) will require changes to the ARTS display software. To the extent practicable, other TIPS functional capabilities will be incorporated in the new TIPS computers, rather than be added to the existing ARTS software.

j. Expandability to Additional Towers. TIPS can readily be extended to the smaller towers within the terminal area, providing them with needed flight data while handling routine communication with the TRACON and local tower.

k. Applicability to All Terminal Areas. TIPS is suitable for all levels of terminal or tower flight activity. The same system hardware elements and computer programs will be used in all cases. Small facilities will have fewer displays and a smaller data base than large facilities. Differences between facilities will also be reflected in adaptation software.

l. Use of Low Cost Technology. TIPS will take advantage of recent digital technology advances such as those which involve large scale integration (LSI). New low cost data processing and display hardware will be used for most TIPS functions, while the present ARTS hardware and software will be used for Radar Controller-related functions.

m. Failure Mode Provisions. TIPS will include a failsafe capability (e.g., redundant equipment) at those facilities where it can be justified. (This will not be provided in the prototype system). At all facilities, a TIPS processing or

communications failure will not affect existing display information, and the failure of one display unit will not affect other display presentations. The failure of any one processor will permit continued operation of TIPS, but at a reduced level of capability.

n. Design Overview

The precise computer/display system hardware configuration is not defined. The FAAs requirements are based upon functional performance requirements. For the purpose of describing the TIPS, a typical configuration is presented here. However, such things as computer architecture, intelligent vs non-intelligent displays will depend upon performance/cost tradeoffs and are to be a part of the TIPS industry proposal, with design innovations strongly encouraged.

The functional prototype TIPS includes a Terminal Flight Data Processing Subsystem, a TRACON Display Subsystem (TRDS), and two Tower Display Subsystems (TDS). The two TDSs will include one local TDS and one Remote (TDS). However, the TIPS prototype system installed at the NAFEC facility will consist of one TDS rather than two TDSs. The prototype TIPS also requires certain changes to the National Airspace System (NAS) enroute and ARTS III computer programs, and a data communications capability between the TIPS, ARTS and enroute computers. The prototype TIPS has the growth capability to add additional Tower Display Subsystem which would contain the same hardware (except for the number of display/data entry devices) and use the same software (except for adaptation changes) as the two initial TDSs.

The Terminal Flight Data Processing Subsystem contains a separate TIPS computer called the Terminal Flight Data Processor (TFDP), which interfaces directly with the collocated ARTS III computer, the host ARTCC computer, the TRDS and the TDS(s). The TFDP will maintain a terminal data base for flight and other non-radar data that integrates locally entered data with flight data provided by the ARTCC. It will also supply flight data to ARTS, the TRDS and the TDS(s) on a timely basis and will route messages to their proper destination.

The TDS and TRDS each contain a capability to update tabular display presentations and process controller inputs. The TDS contains displays and input devices for Clearance Delivery (CD), Flight Data (FD), Ground Control (GC), and Local Control (LC) positions. The TRDS contains displays and input devices for Arrival Data (AD) and Departure Data (DD) positions. Optionally, the TRDS also contains display and data entry devices for CD and FD positions.

The ARTS computer program changes required for the prototype TIPS include those needed to: present flight plan data to Radar Controllers (on their ARTS displays), interface the ARTS computer with the TFDP, provide the ability to handle all FDEP type messages entered on ARTS keyboards, handle flight plans entered from the ARTCC, TIPS or local entry devices, and provide beacon code assignments for VFR and local IFR flights. The enroute (ARTCC) computer program changes required for the prototype TIPS include those needed to: provide full flight plans to TIPS (and ARTS), interface the ARTCC computer with the TFDP, and provide the ability to handled all FDEP type messages over the medium speed (2400 bps) interface. A data communications capability is required which permits the ATC system to operate in either a TIPS or a non-TIPS mode. When operating in a TIPS mode, the TFDP will interface with the ARTCC and ARTS computers via a patch panel, and all data transmitted between the ARTCC and ARTS computers will be relayed by the TFDP. When the ATC system is operating in a non-TIPS mode, the ARTCC and ARTS computers will communicate via the patch panel without involving the TFDP. The existing ARTS-NAS interface will be used for the TIPS/non-TIPS modes.

Figure 1 presents a simplified information flow diagram for the prototype TIPS.

The prototype TIPS contains three major new subsystems: Terminal Flight Data Processing Subsystem, Tower Display Subsystem (TDS); one local and one remote and TRACON Display Subsystem (TRDS).

1. Terminal Flight Data Processing Subsystem

The Terminal Flight Data Processing Subsystem hardware consists of a Terminal Flight Data Processor (TFDP) and its peripherals. The TFDP will interface with the ARTCC and the ARTS computers over 2400 bps data channels. The TFDP will also interface with the TRACON Display Subsystem and up to six Tower Display Subsystems. The TFDP includes the following: 16K sixteen bit words of internal memory, with expansion to at least 100 percent greater than the processing and storage capabilities required for the maximum subsystem configuration, controllers for the TFDP communications; interfaces, Direct Memory Access (DMA) capability, multiple priority interrupts (at least eight) and a computer control panel.

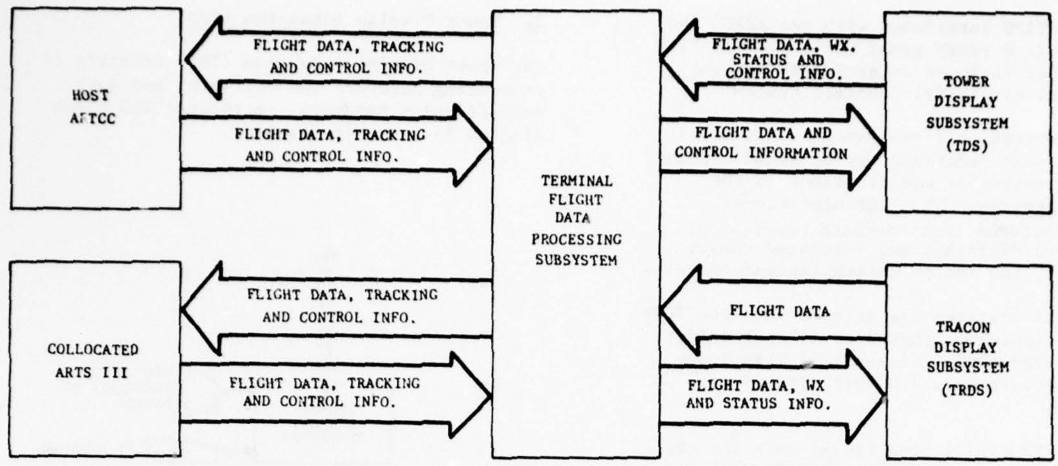

FIGURE 1, SIMPLIFIED TIPS INFORMATION FLOW DIAGRAM

The TFDP peripherals consist of: an Input/Output Terminal (IOT) for entering supervisory messages and printing error and status information, a data storage unit (disk) capable of containing the terminal flight data base, magnetic tape unit to provide for the loading of operational and support programs and data recording, a line printer to support program development and debugging activities and a card reader to support prototype program development and testing activities.

A block diagram showing the TIPS Terminal Flight Data Processing Subsystem hardware and interfaces is presented in Figure 2. The

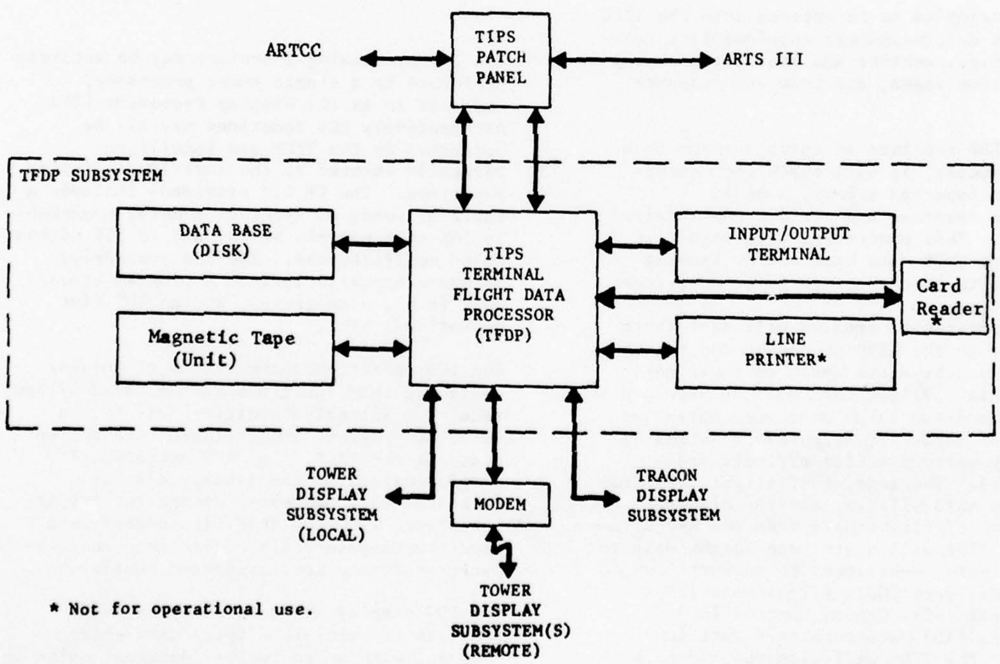

FIGURE 2, TERMINAL FLIGHT DATA PROCESSING SUBSYSTEM

prototype TIPS interfaces with the ARTCC and ARTS III via a patch panel which permits TIPS to be either included or excluded from the operational air traffic control system.

The TFDP operational program is of modular design so that functions may be added without requiring extensive modifications to the existing program. The TFDP operational program performs input message processing, flight data distribution, automated runway assignment, and system monitoring and control.

Operational messages are entered into the TFDP from four sources. They are: 1) Host ARTCC; 2) Collocated ARTS Processor; 3) TIPS Tower Display Subsystem; and 4) TIPS TRACON Display Subsystem.

The host ARTCC will send flight data for the TFDP data base, and tracking and handoff data to be relayed to the ARTS processor. The collocated ARTS processor will send flight data requests and entries for TFDP processing, tracking and handoff information to be relayed to the ARTCC, and flight transfer information to be sent to the TIPS Tower Display Subsystem(s). The TIPS Tower Displays Subsystems will send flight data requests and entries, weather and status information, and ARTS flight transfer information. The TIPS TRACON Display Subsystem will send flight data requests and entries.

Message categories to be entered into the TFDP are: flight data messages; supplementary data messages (e.g., weather and status); tracking and control messages, and test and response messages.

When the TFDP receives an input message from another computer, it will check the message for certain types of errors, send an appropriate response and perform the required processing. This processing will result in updating the TFDP data base and/or sending output data to another computer or subsystem.

The TFDP operational program will distribute flight data to the ARTS processor and to the TIPS display subsystems based on their need for this data. Flight data will be supplied to the ARTS processor based on tower controller actions (for departure flights) or estimated time at any entry fix (for arrivals and overflights). The sending of flight data from the TFDP to ARTS will replace the direct transmission of flight data from the ARTCC to ARTS. The TFDP will distribute flight data to the TIPS display subsystems to support Clearance Delivery (CD), Flight Data (FD), Local Control (LC), Ground Control (GC), Arrival Data (AD), and Departure Data (DD) positions. The TFDP will also respond to a specific request for flight data from any TIPS or ARTS data entry/display position in the terminal area.

2. <u>Tower Display Subsystem (TDS)</u>

The Tower Display Subsystem (TDS) consists of processing hardware and software, and data entry/display hardware. A typical TDS block diagram is shown in Figure 3.

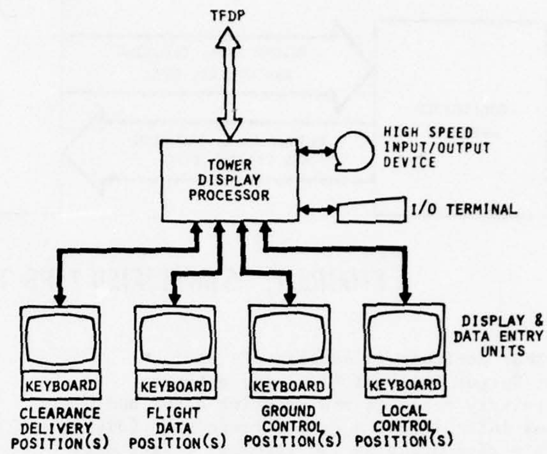

FIGURE 3, TOWER DISPLAY SUBSYSTEM

The TDS processing functions may be entirely performed in a single tower processor, referred to as the Display Processor (DP). Alternatively the functions may all be performed by the TFDP and intelligent terminals located at the individual display positions. The DP (if provided) includes a basic 8K words of internal memory, expandable to 16K on a plug-in basis, and to 32K without major modifications. The TDS processing hardware may also include a program storage unit (e.g., a cassette), and an IOT (for operational use).

The TDS operational program is of modular design so that functions may be added without requiring extensive modifications to the existing program, and is loaded via action taken at the TFDP. The TDS operational program maintains the tabular display presentations, processes controller inputs, interfaces with the TFDP (if located in a separate computer) via modems or direct, and performs system monitoring and control.

The TDS display and data entry hardware consists of multiple display/data entry devices, with up to twelve identical units in a single tower. Each display/data entry devices includes: a tabular display, data select/transfer device, and keyboard.

Each tabular display contains a sufficient number of lines of alphanumeric information to display the flight, weather and status data; each line contains nominally 68 characters. The character set includes the twenty-six capital letters, the digits 0 through 9, and seventeen special symbols, with growth to 64 total characters. The nominal character size is 0.18"H x 0.14"W. The display also has a cursor symbol.

The display is designed to provide good contrast under high ambient light conditions as is found in tower cabs.

Each display position contains a data select/transfer device which provides a "quick action" capability for performing commonly used functions. This data select/transfer device is used to request the display of flight data, transfer flight control to another selected position, enter certain types of flight data and, where appropriate, change the order in which displayed data is presented. This device may be a touch sensitive overlay on the display surface, or it may contain push-buttons.

Each display position includes an ARTS III type keyboard with special function keys for the TIPS functions. The keyboard is used to enter alphanumeric information and also provides the capability for performing infrequently used functions.

3. <u>TRACON Display Subsystem (TRDS)</u>

The TRACON Display Subsystem (TRDS) consists of processing hardware and software, and display/data entry hardware. A typical TRDS block diagram is shown in Figure 4.

The TRDS processing functions may be performed in a separate TRDS processor, in intelligent terminals, or in the TFDP. In any case, the TFDP IOT will be used for entering supervisory messages and printing error and status information related to the TRDS. A program storage unit may be included for loading operational and support programs; alternatively, program loading may use the Terminal Flight Data Processing Subsystem hardware.

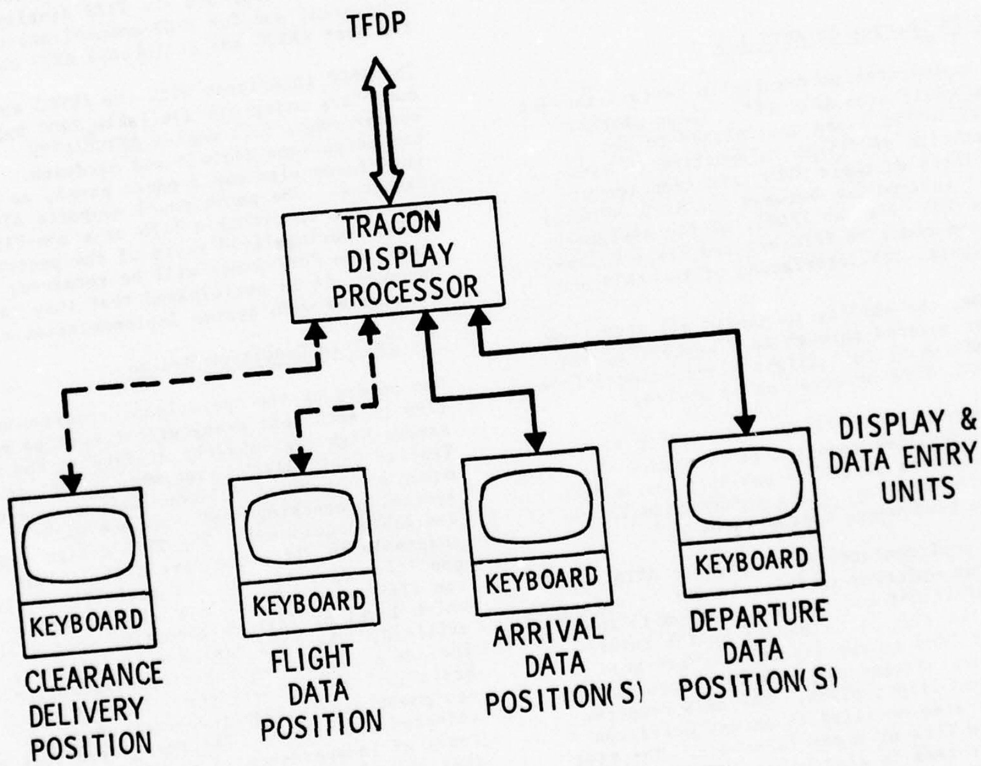

FIGURE 4, TRACON DISPLAY SUBSYSTEM

The TRDS software will a) generate and update display presentations for the Arrival Data (AD) and Departure Data (DD) positions, b) process AD and DD data entries and requests, c) interface with the Terminal Flight Data Processing Subsystem computer program and, d) perform basic system monitoring and control functions.

The processing performed by the TRDS software will be similar to that performed by the TDS software, except that it will relate to AD and DD displays and data entries rather than to tower displays and entries. The TRDS software will maintain planning lists of arrivals and overflights (organized by entry fix) on the AD displays, and planning lists of departures (organized by departure airport) on the DD display.

As an option, the TRDS software can accommodate Clearance Delivery (CD) and Flight Data (FD) positions, (e.g., for a satellite airport) In this case, the TRDS software performs those functions which are performed by the TDS software in support of the CD and FD positions.

The TRDS display and data entry devices consists of two units which are identical to those provided with TDS, except that some "quick action" and keyboard entry functions will be different.

4. TIPS Changes to ARTS III

TIPS implementation results in certain changes to the collocated ARTS III. These changes involve software and are related to the presentation of flight information to Radar Controllers on their PVDs, the transfer of control information between the ARTS computer and the TDS (via the TFDP), of the assignment of beacon codes to TIPS entered VFR and local IFR flights, the interfacing of the ARTS and the TFDP, the ability to handle all FDEP type messages entered through ARTS keyboards, and the handling of full flight plans entered from the ARTCC, TIPS or local entry device.

The presentation of flight information to Radar Controllers consists of providing the "alternate data switch" capability and a full flight plan readout, using information in the TIPS data base where appropriate.

With the implementation of TIPS, the ARTS software is modified to initiate the transfer of arrival flight control information to the tower at the time it is needed by the tower controller, and to supply computer-assigned beacon codes in response to a TFDP request for TIPS entered flight plans. The ARTS computer program is also modified to permit operation in either a TIPS or a non-TIPS mode. The TIPS computer program is also being developed to process all FDEP type messages entered through ARTS keyboard and to process full flight plans entered from the ARTCC, TIPS, or local entry device.

5. TIPS Changes to NAS Enroute

Implementation of TIPS results in certain changes to the NAS enroute software. These changes result from a) the requirement for the enroute software to operate with several terminal area configurations and b) additions and modifications to the messages transmitted between the ARTCC and the terminal area.

The ARTCC will operate in a TIPS/ARTS mode when both terminal systems are operating normally. However, it will operate in a TIPS-only or an ARTS-only mode if one of the systems has failed or been otherwise shut down.

With TIPS operational, the ARTCC will send full flight plan data to the TFDP, rather than basic flight plan data to ARTS as at present. The ARTCC will handled all FDEP type messages received from the terminal over the medium speed (2400 bps) interface.

6. Data Communications

Data communications hardware and circuits are provided for internal TIPS communication between the TFDP and the TIPS display subsystem, and for TFDP communications with the host ARTCC and collocated ARTS computers.

The TFDP interfaces with the ARTCC and ARTS computers using the available 2400 bps synchronous, full duplex ARTCC/ARTS communications circuit and hardware. These interfaces also use a patch panel, as shown in Figure 2. The patch panel supports ATC operation in either a TIPS or a non-TIPS mode. During field tests of the prototype TIPS, the FDEP lines will be retained; however, it is anticipated that they can be eliminated with system implementation of TIPS.

7. Failure Condition Design

The nature of the operational requirements for TIPS is such that every effort must be made to assure high availability of data to the Air Traffic Controller. Even when conditions occur that prevent full operational use of the system, processing must continue with available equipment. The TIPS design is adaptable to different levels of failure condition operations. The activity levels of the TIPS terminal facility will determine which level of failure condition mode will be utilized. The TIPS design will initially include a simplex equipment configuration with basic fail soft provisions. Production equipment may include redundant units at selected facilities. The design provides a level of independence in each subsystem so that when failure occurs in one subsystem, other subsystems shall continue to operate at a level sufficient for smooth transition to a failure mode operation.

SUMMARY

The TIPS program has been planned to meet the need to replace the FDEP equipment with a modernized automated system. The TIPS system is expected to automatically distribute and display flight data and other operational information needed by the air traffic controllers in ARTS III TRACONS and towers.

An innovative system design is expected that will provide productivity, safety and efficiency benefits.

REFERENCES

1. ARTS III Enhancements Costs and Benefits, FAA-AVP-75-3, September 1975

2. Terminal Information Processing System (TIPS) Engineering Requirement, FAA-ER-D-120-006.

DIGITAL REMOTING FOR AIR TRAFFIC CONTROL TERMINAL AREAS

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BIOGRAPHY

Archie Millhollon is a project engineer in Air Traffic Control (ATC) automation, working in the Terminal Branch of the ATC Systems Division, Systems Research and Development Service. He has been working in terminal automation for 5 years, and was involved with the technical development of the ARTS III automation program which was implemented nationwide in 1975. Mr. Millhollon first came to SRDS in 1965 where he worked on several communications and automation projects. He holds a B.S.E.E. degree from the University of California at Berkeley.

ABSTRACT

The FAA's research and development staff is chartered with continually investigating the application of automation features to air traffic control. This paper describes a current project that expands on Automated Radar Terminal System (ARTS) III A to accommodate digital radar remoting and remote display operation. The system as described is as specified by the FAA and as designed by the Sperry UNIVAC, Defense Systems Division.

INTRODUCTION

Since the early 1960's the Federal Aviation Administration (FAA) has been using digital system technology to assist in the control of air traffic. As the technology has become more and more economical in application, the FAA has in turn pressed on to more sophisticated air traffic control (ATC) systems. This paper presents a description of a digital ATC system soon to undergo evaluation at Tampa, Florida. The expected benefits are economical methods for providing expanded radar service in the ATC terminal areas. The economies accrue from the ability to digitally extract aircraft target information from the primary and secondary radar videos and distribute the information via 4800 bits/per second (b/s) data circuits instead of expensive 8 MHz video channels.

ARTS III Systems

To put the Tampa ARTS IIIA remoting system into perspective, first consider the basic ARTS III system. In its single sensor form (input from one secondary radar system), the ARTS III consists of 1 UNIVAC input/output processor (IOP) and 2 or 3 memory modules (MM) (30 bit words) and 6 to 10 time shared (T/S) displays. A dual sensor system has 2 IOPs, 3 MM and 8 to 122 T/S displays. The ARTS III is a beacon only tracking system that can handle about 250 aircraft. The secondary radar data is processed, tracked and displayed in association with alphanumeric data, which provide aircraft identification, Mode C derived altitude, target velocity and/or radar beacon code readouts to the operator (Air Traffic Controller). The system permits the operator to enter data and selectively display, alter or delete data consistent with operational needs. Primary video and secondary radar video are displayed concurrently with the symbolic and alphanumeric data. The present ARTS III system also provides the capability of data/message interchange with Air Route Traffic Control Centers (ARTCC) computer systems.

The expanded ARTS III is called the ARTS IIIA system. It is the latest step in meeting increasing traffic demands in terminal areas. The single sensor version consists of two IOPs, 6 MM, a disc subsystem and 6-10 T/S displays. A dual sensor system will have 4 IOPs, 10 MM, a three drive disc subsystem and 8-20 T/S displays. The ARTS IIIA system provides eight additional capabilities as

listed below:

a. Radar Target detection and processing
b. Beacon - radar correlation and tracking
c. Improved aircraft tracking subprogram
d. Multiprocessor executive
e. Hardware and software expansion capability
f. On-line continuous data recording
g. Failure recovery and reconfiguration (failsoft)
h. Automatic overload sensing and protection

ARTS IIIA Remoting System

The ARTS IIIA Remoting System is a IIIA system with the addition of radar remoting and remote display capabilities. Remoting requires: a communications multiplex controller (CMC) to interface the data circuits with the IOP, a sensor receiver and processor (SRAP) to digitize the primary and secondary radar videos, a Tower Cab Digital Display (TCDD) and a Remote Display Buffer Memory (RDBM). The RDBM receives the digital display data from the host ARTS IIIA system, stores the data and provides the TCDD refreshing. Figure 1 is a block diagram of an ARTS IIIA remoting system. Table 1 below identifies all the abbreviation used on the block diagram:

Table I HARDWARE ABBREVIATIONS

MM -	16K (30 bit word) Memory Module
CMA -	Central Memory Access, a buffer driver between the IOPs and memories
RFDU -	Reconfiguration Fault Detection Unit, provides for automatic and manual partitioning of memories and processors.
IOP -	Input/Output Processor, main computing element for the ARTS III
ICA -	Interfacility Communications Adapter for 2400 bit/second data link to air route traffic control center.
IMT -	Integral Magnetic Tape adapter for 7 track Potter tape drive.
TTT -	Teletype adapter for ASR-37 console typewriter.
PSM -	Peripheral Switch Module provides for switching ICA, IMT and TTY between two IOPs.
MDBM -	Multiplexed Display Buffer Memory provides display refresh memory for the DEDS.

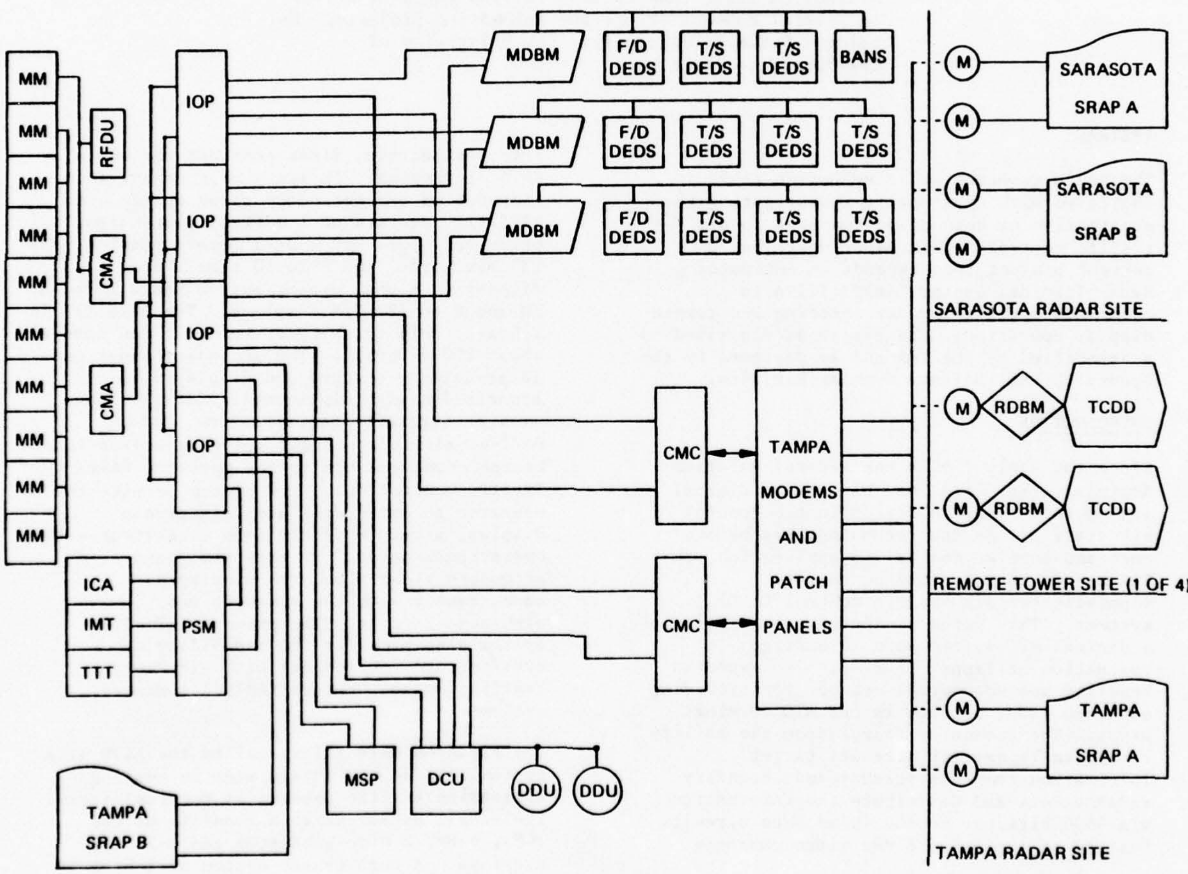

FIGURE 1, ARTS IIIA REMOTING SYSTEM

F/D DEDS - Full Digital Data Entry Display subsystem, keyboard and full digital display for ATC controller use.
T/S DEDS - Time Shared DEDS, keyboard and dual mode (broadband video and alphanumerics during radar dead time) display for ATC controller use
BANS - Brite Alphanumeric System, A TV mode display bright enough for tower cab use and has full alphanumeric capability with keyboard
CMC - Communications Miltiplexer Controller, provides modem link interface for up to 16 full duplex devices with speeds up to 9600 bits/second
MSP - Medium Speed Printer, a 300 line per minute printer
DCU - Disc Control Unit controls up to 16 disc drives
DDU - Disc Drive Unit, a 100 Megabyte per disc pack unit that will be used to store recovery module, backup program library, on call programs, critical data and continuous data for ATC history
RDBM - Remote Display Buffer Memory, a remote interface unit between the IOP and TCDD. Refreshes the TCDD and formats keyboard messages for return to the IOP
TCDD - Tower Cab Digital Display a bright full digital display for tower cab use
SRAP - Sensor Receiver and Processor, a primary and secondary radar digitizer and target detection unit

Prior to discussing the software, it will do well to review the hardware design in more depth. Five of the hardware devices are somewhat unique to this type of system. They include the SRAP, RDBM, TCDD, MDBM and CMC. The other devices like the MM, IOP, disc, etc. are common items found in most data processing systems.

SRAP

The SRAP is comprised of three distinct units, the Radar Data Acquisition Subsystem (RDAS), the Beacon Data Acquisition Subsystem (BDAS) and the Common Processing Subsystem (CPS). Figure 2 illustrates the system configuration.

The function of the RDAS is to detect and transfer aircraft target and weather data derived from search radar video returns. The BDAS provides detection and transfer of aircraft target data derived from beacon transponder replies. The CPS provides correlation and merging of radar and beacon target reports and output of target and weather data to the IOP or modems.

The RDAS and BDAS are each composed of two equipment groups, a front end hardware group referred to as a radar/beacon extractor (REX/BEX) and a radar/beacon microcontroller (RMC/BMC). The CPS also is composed of two equipment groups, a common microcontroller (CMC) and a Serial Interface Module/Parallel Interface Module (SIM/PIM) tailored for either serial or parallel data transmission. The microcontrollers are similar for the RDAS, BDAS, and CPS, except for the unique program instructions contained in the respective read-only memories.

Radar Extractor - The Radar Extractor (REX) receive normal and MTI video and a pretrigger from the radar receiver, and Azimuth Change Pulses (ACPs) and Azimuth Reference Pulses (ARPs) from the Azimuth Pulse Generator (APG). Outputs to the Radar Microcontroller (RMC) include a report for each detected target, an azimuth count transmitted once each sweep, single sweep clutter sum data, and alarm messages. In addition to these signals, the REX provides several varieties of tests video for use in fault isolation. The RMC supplies clutter map data for normal MTI video selection and various REX parameter control settings. Figure 3 shows the block diagram for the REX.

Radar Microcontroller (RMC) - The radar microcontroller (RMC) firmware controls the

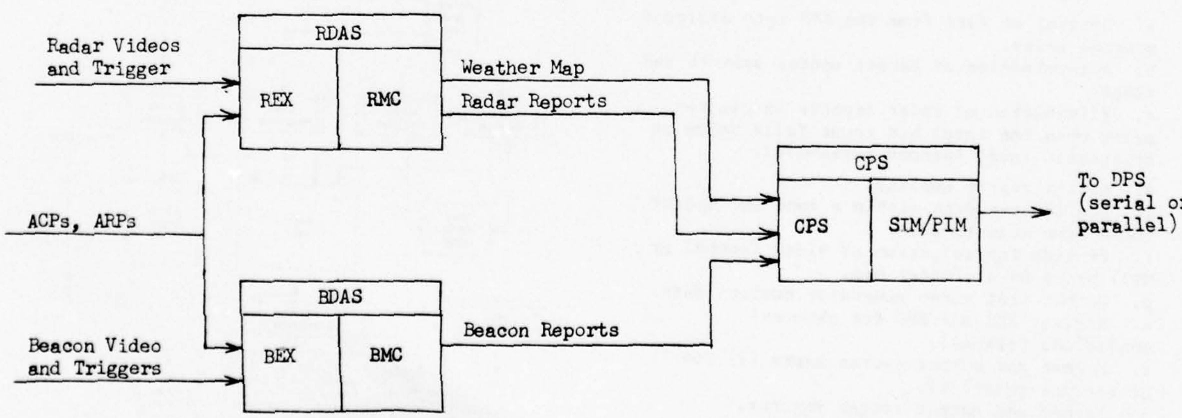

FIGURE 2, BLOCK DIAGRAM OF SENSOR RECEIVER AND PROCESSOR

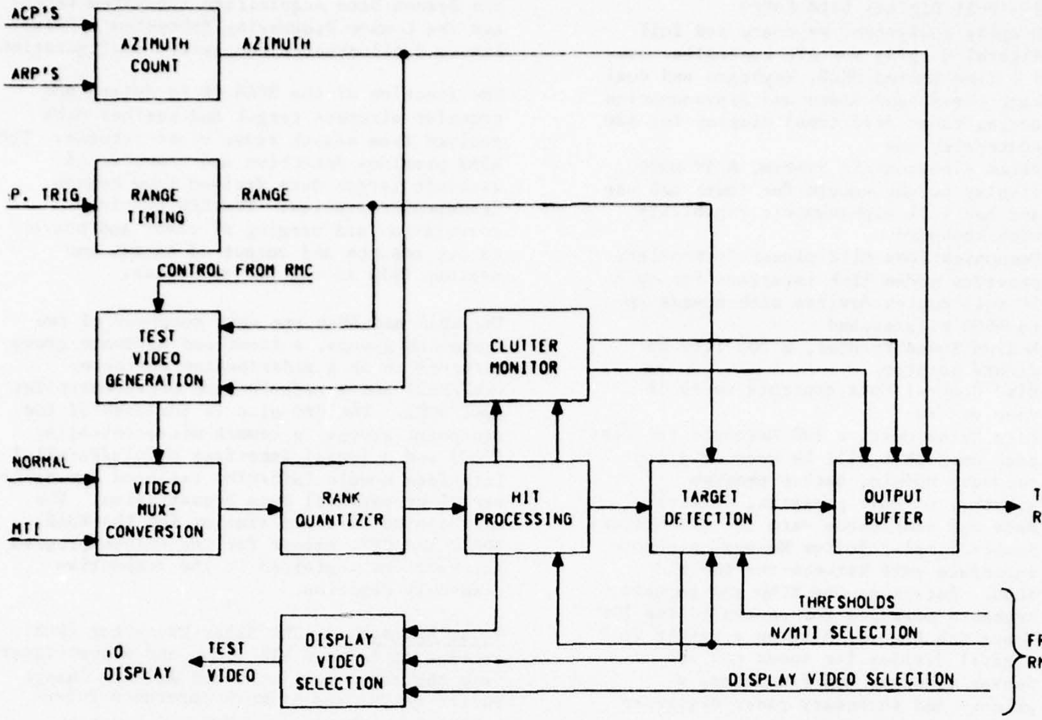

FIGURE 3, BLOCK DIAGRAM OF RADAR EXTRACTOR

data flow between the Radar Extractor (REX) and the RMC, processes the incoming data, and formats and outputs the processed data. Data received from the REX consists of azimuth data, target report words, weather data, and alarms. Data sent from the RMC consists of declared targets, weather map data, sector marks, and alarms. The RMC also controls the selection of video type, i.e., normal video in clear, MTI video in clutter. A summary of the microprogram processing task is given below:

a. Control of data from the REX into assigned storage areas.
b. Determination of target center azimuth and range.
c. Elimination of radar reports in clutter areas when the total hit count falls below an acceptable level (second threshold).
d. Assign report quality.
e. Sum clutter data within a zone and update these from scan-to-scan.
f. Provide for selection of video (normal or MTI) based on a clutter map.
g. Output test video generator control data.
h. Monitor REX and RMC for abnormal conditions (alarms).
i. Format and output sector marks (11.25° of antenna rotation).
j. Format and output target reports.
k. Format and output weather data.
l. Format and output alarm data.
m. Provide for output to the First In/First Out (FIFO) memorie(s).
n. Allow for manual inspection and change of source and destination registers.

The overall control and data flow is dipicted in Figure 4.

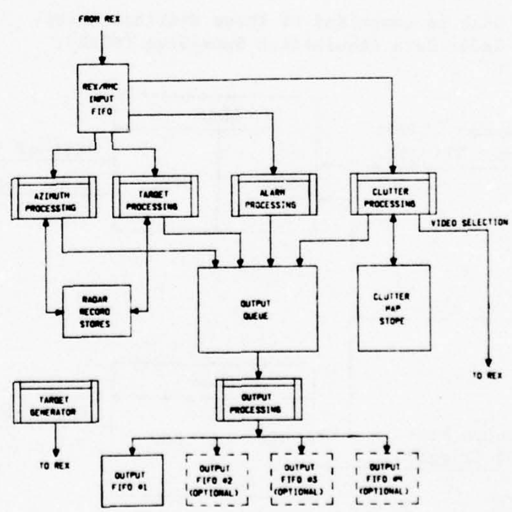

FIGURE 4, RADAR PROCESSING DATA FLOW

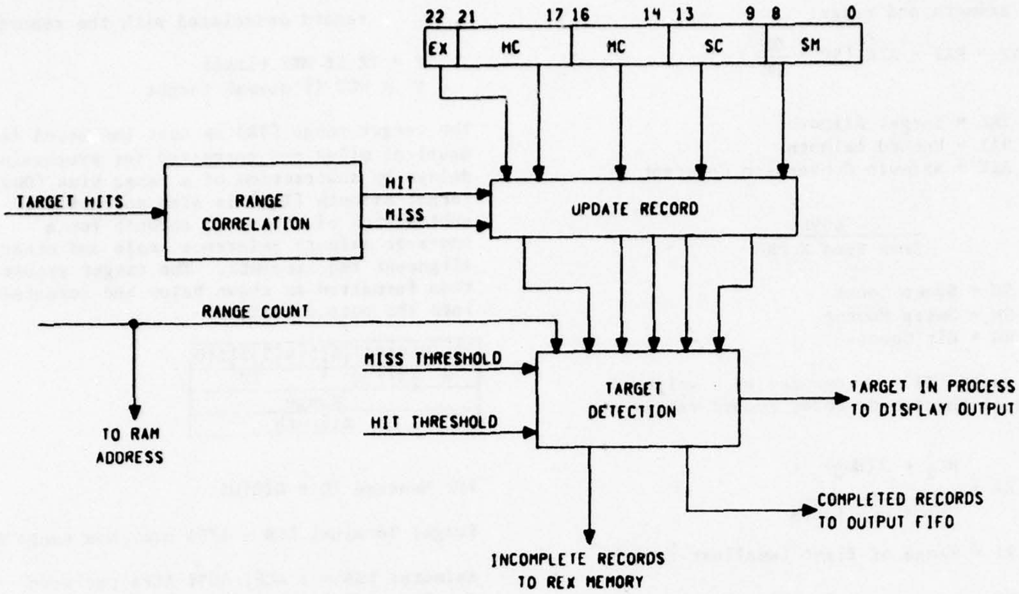

FIGURE 5, BLOCK DIAGRAM OF SRAP TARGET DETECTION

The SRAP Radar Target Detection logic group is in the REX and is illustrated on Figure 5. The input to this group is selected target hit data, one bit per range cell, from the Hit Processing group. An additional input comes from the REX memory (Figure 6). The REX memory contains storage for a possible record at each range cell (2048 total). Each record utilizes 23 bits of a 27 bit memory word. Information contained within the record is as follows:

HC = Hit Count, number of correlating hits since start of the record.

MC = Miss Count, number of consecutive misses since the last hit.

SC = Sweep Count, number of sweeps the record has been active, beginning with 1 at the first hit.

SM = Sweep Moment, sum of sweep counts where hits occur.

EX = Extended Record (more than 31 sweeps long).

A record range is defined by its position (address) in memory. Consequently, the range counter is utilized to form the memory address.

Once a target record is established, it remains in process until target end is detected. Target end is declared when a sufficient number of consecutive misses have been encountered. At target end, the hit count is examined. If the hit count exceeds a threshold, the record is transferred to the Output Buffer. Otherwise, it will be discarded. In either case, the record is deleted from the REX memory.

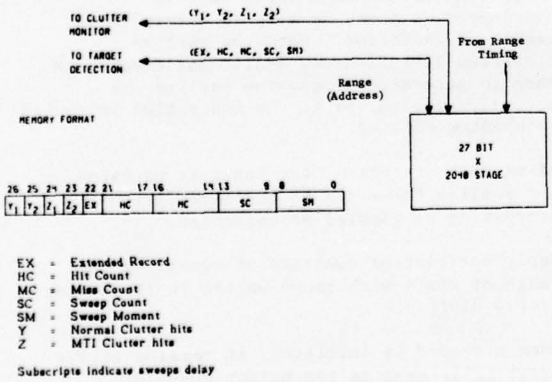

FIGURE 6, BLOCK DIAGRAM OF REX MEMORY LOGIC

SRAP radar target processing is done in the RMC. A range order Target Record Store Buffer is provided to hold reports from the REX for consolidation of range and azimuth splits. The input FIFO being empty results in the processing of reports and records from the Record store to the Output Queue. The Multiple Report Indicator (MRI) bits of the report will indicate if there are additional reports in the REX which will correlate with this report.

The correlated records are then processed for Target Azimuth (TAZ) and Range (TR). The following formula shall be used to compute

target azimuth and range:

$$TAZ = RAZ - AZK \left(SC - \frac{SM}{HC}\right)$$

where: TAZ = Target Azimuth
RAZ = Record Azimuth
AZK = Azimuth Conversion Constant

$$\frac{4096}{\text{Scan Time X PRF}}$$

SC = Sweep Count
SM = Sweep Moment
HC = Hit Counts

Target range (TR) is computed by a weighted average of the two or three record ranges as follows:

$$TR = R1 + \frac{HC_2 + 2(HC_3)}{HC_1 + HC_2 + HC_3}$$

where: R1 = Range of first (smallest range) record
HC_n = Hit count for record n

If the report hit count (largest of associated record values) is below a parameter (T2 maximum) the record is considered for a possible second threshold test. The range and azimuth (TR and TAZ) are examined to determine which clutter zone the report lies in, and the corresponding clutter zone examined to determine if MTI is selected. If MTI is selected, then a second threshold test is applied to the report hit count. The threshold for this purpose is computed as follows:

$$T2 = T_0 + C_1 (C_0 - IHS) \text{ for } IHS < C_0$$

$$T2 = T_0 \text{ for } IHS \geq C_0$$

Where: T_0, C_0, C_1 = Parameters
IHS = Isolated hit sliding window sum (Estimate of Clutter Correlation).

Target report hit counts which fall below this threshold are discarded. This test applies only to reports which lie in MTI zones. Reports in normal video zones are not subject to second threshold testing. Reports within the expected test target azimuth, 16 $\pm$ 3 ACPS are checked to determine if they agree with the test target range + 1 RC. The test target bit shall be set for this target output and a test target found flag set for detection by the Test Target verification.

A Report Quality is assigned in accordance with the following formula:

$$Q = HC - T \text{ if } HC - T \leq 7$$

$$Q = 7 \text{ if } HC - T > 7$$

where: HC = Maximum target hit count of any record associated with the report.

T = T2 if MTI target
T = HCT if normal target

The target range (TR) is next converted into nautical miles and corrected for processing delays by subtraction of a range bias (DR). Target azimuth (TAZ) is also corrected by subtraction of a bias to account for a non-zero azimuth reference angle and other alignment requirements. The target report is then formatted as shown below and inserted into the output buffer.

11	10	9	8	7	6	5	4	3	2	1	0
N		T	Q			ID					
Range											
Azimuth											

ID: Message ID = 010101

Range: Terminal LSB - 1/64 n.m., Max Range 64 NM

Azimuth: LSB = 1 ACP, 4096 ACPs per scan
Q = Report Quality 0-7
T: Test Target
N: Not Used

Beacon target processing is done in the BMC. The range/code words coming from the BEX are merged with a record in the record store or a new record is created (see Figure 7). The merging process is based upon range correlation and is described in the following paragraphs. Replies are alternately merged from Record Store A to B, then B to A, based on the indices set during azimuth word processing.

Garble sensing is peformed first. If the SPI bit is set and the reply ranges are within 24.95 usec) or if the SPI bit is not set and the reply ranges are within 197 RCs (20.4 usec) the trains are overlapped and may be garbled. In order to determine if this situation exists, the last three received during a given sweep are examined.

If a reply pair is not overlapped, it is passed on to determine correlation with previous sweep returns. When a reply pair is overlapped, a check is made to determine if garble is indicated. When the garbled condition is indicated, additional checks are made to determine if the two replies are actually garbled, or if the indication is caused by phantom replies.

After each iteration, the logic is repeated and replies forwarded to the correlation processing as garbled or ungarbled.

Reply correlation consists of comparing the range of reply with range values in the Beacon Record Store.

Once a record is initiated, it remains active until it is sent to the output queue or discarded. The miss count (MC) is compared to

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Word 6K	X	S	V_a		3/A Code											
Word 6K+1	R	F	V_c		C Code											
Word 6K+2	Range															
Word 6K+3	U	MC						HC								
Word 6K+4	SM															
Word 6K+5	SC															

K varies from 0 to 44

3/A and C code same as in FIFO input

R = ring-around flag

S = SPI indicator

V_a = 3/A Code Validity
- 0 = All replies are garbled
- 1 = One reply is not garbled
- 2 = One garbled reply and one ungarbled reply have identical codes
- 3 = Two ungarbled replies have identical codes.

V_c = C Altitude Validity
- 0 = No replies or all replies garbled
- 1 = One reply is not garbled
- 2 = One garbled reply and one ungarbled reply have identical altitudes
- 3 = Two ungarbled replies have identical altitudes

Range = target range (LSB = 103.5 nsec)

F = First Record at this range when set.
MC = No. of consecutive misses after last hit
HC = No. of hits detected during target run
SM = Sum of sweep numbers in which a hit occurred
SC = Sweep count: Set to 1 at 1st hit, incremented by one each sweep.

X = Unmanned aircraft when set
U = Unused

FIGURE 7, BEACON RECORD FORMAT

the miss threshold system parameter MT, and if greater, the following checks are made: If hit count equals 1, the record is discarded. If not, and the sweep count (SC) is less than the Minimum Sweep Threshold (MST), then the record is retained for checks to determine if it exceeds the Hit Threshold (HT). If the hit count exceeds the threshold, the record is transferred along with the current azimuth count to the output queue. If the hit count does not exceed the threshold, the record is discaded as fruit.

The BMC processes the beacon target report center azimuth (TAZ) using the "center of density" technique according to the following equation:

$$TAZ = RAZ - AZK \quad (SC - SM/HC) - DAZ$$

where: RAZ = record azimuth; value of azimuth count when miss count equaled miss threshold

AZK = conversion constant = 4096/scan time X PRF
AC = sweep count
SM = sweep moment
HC = hit count
DAZ = azimuth bias

Target range (TR) is converted to nautical mile units and adjusted for processing delays.

$$TR = RK \cdot R - DR$$

where: RK = conversion constant, microseconds to nautical miles
R = record range
DR = range bias

The target range is converted to nautical mile units by multiplication of the proper conversion factor (nanoseconds to nautical miles). The balance of the target message is formatted as specified in Figure 8. The message is then inserted into the output FIFO and the target record cleared from the output queue.

11	10	9	8	7	6	5	4	3	2	1	0
13	12	T	Q			ID					
Range											
Azimuth											
Code											
Rr	Altitude										
BHC					R	X	S	V_c		V_a	

ID: Message ID = 001111
Range: Terminal LSB = 1/64 N.M., Maximum Range 64 N.M.
Q: Report Quality 0 - 7
Azimuth: LSB = 1 ACP, 4096 ACPs per Scan
S: SPI
V_a: 3/A Code Validity
- 00 - Replies are all garbled
- 01 - One reply is not garbled
- 10 - One garbled reply and one ungarbled reply are identical
- 11 - Two ungarbled replies are identical

3/A Code: 00000 - 7777 (octal) code value
R: Ring Target Indicator 1-Ring, 0-Normal
V_c: Mode C Validity
- 00 - No replies or all replies are garbled
- 01 - One reply is not garbled
- 10 - One garbled reply and one ungarbled reply identical
- 11 - Two ungarbled replies are identical

Altitude: Mode C altitude, 2^0 = 100 feet, 2^8 = 25,600 feet
Maximum altitude 99,900 feet $(1747)_8$
Bit 2^{10}:
sign of altitude 0 = pos, 1 = neg
-1777_8 = Illegal altitude code
-1776_8 = All zero altitude code

T: Test Target
Rr: Radar Reinforced
BHC: Beacon Hit Count
X: Code bit indicating unmanned aircraft
12 and 13: Range Bits 2^{12} and 2^{13}

FIGURE 8, OUTPUT WORD FORMATS

In the CPS, the incoming radar reports are compared with beacon reports. If the range of the two reports are within a range parameter (MRNG) and the azimuths are within an azimuth parameter (MAZ) in ACPS, then the radar report is merged into the beacon report to form a radar reinforced beacon report. The range and azimuth of the merged report are linear combinations of the two ranges and azimuths as follows:

$$R_M = RXP(R_B) + (1 - RXP)(R_R)$$
$$A_M = AXP(A_B) + (1 - AXP)(A_R)$$

Where RXP and AXP are system parameters based on a minimum variance estimate. The output of the CPS goes via the serial interface to the modems and data circuit and arrives at the CMC.

Communications Multiplexer Controller (CMC)

The CMC can multiplex any combination of up to 32 plug-in simplex transmit or receive peripheral interface adapters with either of two ARTS III Input/Output Processors (IOPs). The CMC consists of a multiplexer, standardized plug-in facilities to accommodate a variety of interface adapters, and a self-contained power supply. A block diagram of the CMC is shown on Figure 9.

Two interface adapters are currently used in the CMC. The SRAPA for simplex serial operation, and the CTA/CRA for full duplex operation are described as follows:

a. Sensor Receiver and Processor Adapter (SRAPA). The SRAPA will provide a simplex interface for 12 bit plus parity (13-bit frame) serial data input in 1, 2, 3 and 6 frame messages lengths as sent by a remote SRAP. SRAPA operation will be synchoronous at data rates up to and including 9600 bps with clock pulses provided by the modem or, during test mode, by the CMC test clock.

b. Communication Transmitter Adapter (CTA) and communications Receiver Adapter (CRA). - The Communications Transmitter adapter and the Communications Receiver Adpater designs are located on a single board to provide a full-duplex, character oriented, CIDIN interface for command selected 8-bit (no parity) or 16-bit (15 data bits plus parity) synchronous serial communications. Message lengths are variable in exact multiples of the selected character length between 32-bits and 2040 bits. Synchronous operation is from 2400 bps up to and including 9600 bps with clock pluses provided by a modem or 2400, 4800, or 9600 bps with clock pulses provided by CMC test clock when in the test mode.

To accomplish all that is required of the multiplexer in the CMC and keep the number of boards within the physical limits of the design, devices of a family of LSI logic supplied by Advanced Micro Devices, Inc. of Sunnyvale, California are used. The family of logic devices is called the AMD 2900 series, of which the four-bit bipolar microprocessor device, AMD 2901, are cascaded to form the 16-bit microcontroller used in the multiplexer. Some of the reasons for selecting the AMD 2900 logic devices include the following:

1. Partitioned to permit combining only the functional elements needed for the CMC application.
2. Unburdened with capabilities not needed or wanted in the CMC design which would add to the cost and board space required.
3. Instruction repertoire is designed by the user, thus, micro-instructions can be tailored and limited to CMC requirements.
4. Fast memory cycle times, nominally 65 nanoseconds.
5. Schottky TTL logic technology which requires low power.
6. Fully compatible with the TTL MSI devices required for other multiplexer functions.
7. Available from several sources.
8. Has been used successfully for high-speed microcontroller applications.

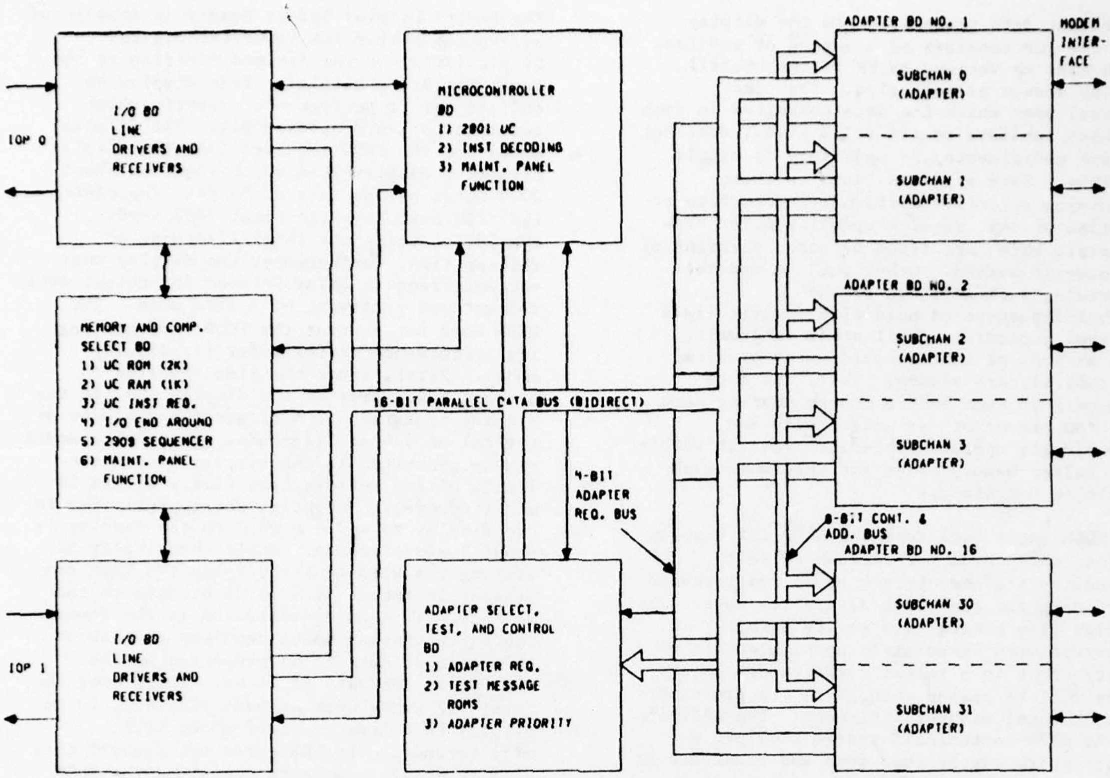

FIGURE 9, SIMPLIFIED CMC BOARD AND LOGIC FUNCTION DISTRIBUTION

The firmware necessary for microcontroller operation in the miltiplexer resides in 2K of solid-state read only memory (ROM) located on the multiplexer's memory and computer select board. A solid-state 1K random access memory (RAM) is located on the same board to provide for microcontroller read and write operations in temporary storage. Firmware includes an operational executive program to control the various routines which perform the miltiplexer's operational functions. In addition, a test executive program is included to control the routines needed to perform the CMCs internal test functions. The executive programs and their routines are microcoded using the instruction repertoire specifically designed for the microcontroller in the CMC application. Once the programs are written, tried, and considered devoid of problems, they are written into the ROM by a process known as "burn-in". Altering the burned-in firmware to accommodate newly designed routines for future adapters will require replacement of the existing ROM with a new ROM containing the latest firmware.

Multiplexed Display Buffer Memory (MDBM) - The MDBM functions in either the time shared or all digital ATC system by receiving lists of display commands from one of two processor output channels, storing them for sequential read out to a display or readback the processor input channel upon request. The MDBM provides the following capabilities:

1. Continual display refresh in the event of a Primary Processor failure.
2. Reduction in I/O channel requirements.
3. Reduction in system I/O data transfer requirment.
4. Reduction in main memory requirements.
5. A means to run I/O channel confidence tests under the multiprocessor executive program or during a recovery cycle of the failsafe ARTS configuration.

The MDBM enables the display to continue to present alphanumeric data to the DEDS in the event of a primary processor failure. Thus, the visual information available to the controller at the time of the failure is not lost during either manual or automatic reconfiguration and restart of the system. Other desirable benefits obtained through implementation of the MDBM are a reduction in processor I/O channel requirements from 8 to 2 per 4 display group (assuming dual channel configuration), a significant reduction in output transfer between the processor and displays (releasing these output transfer main memory references for processing tasks), and release of main memory locations for implementation of additional functions.

The output data transmitted to the display from the IOP consists of a series of sublists which make up various parts of the overall display screen presentation. The time interval over which the data contained in each of these sublists remain valid (i.e., does not require modification or updating) is highly variable. Some sublists, such as those containing aircraft positional information or the time of day, require updating after time intervals which are fixed by other portions of the overall system. Other sublist update intervals, such as those of the arrival-departure or hold alphanumeric lists are semi-periodic. Still other intervals, such as that of the keyboard entry preview are sublist, are random. Thus, the data structure of each buffer memory must be such that the processor can selectively and conveniently update each unique sublist within each buffer memory, when and only when such update is necessary.

The MDBM input data from the ARTS III Display is four data words per refresh cycle to transmit positional (track ball) and keyboard entry data for the three data entry sets. The display also generates a parity error interrupt word immediately upon detection of a parity error in a refresh data word. These words will be passed through to the processor input channel without buffering. The addition of the MDBM to the ARTS system provides a device which can be read into and read back at processor compatible I/O rates for on-line confidence checks of the four channel I/O groups.

The MDBM is capable of communicating with one of two processor I/O channels for operation in a failsoft automatic reconfiguration system.

Remote Display Buffer Memory (RDBM) - The RDBM executes either the time shared, or all digital remote tower display commands from the host ARTS III site over communication lines, storing data for sequential read out to a display or readback to the processor input channel upon request. The RDBM will provide the following capabilities:

1. Continual display refresh in the event of a Data Processing System or communication link failure.
2. Reduction in I/O channel requirements.
3. Reduction in main memory requirements.
4. A means to run I/O channel confidence tests under the multiprocessor executive program or during a recovery cycle of the failsafe ARTS configuration.
5. Internal processing for the trackball position symbol, keyboard preview entries, range ring selection for the display and tabular list relocation.
6. Expansion capability to provide storage for remote site RDBM and display diagnostics.
7. A means to turn on and turn off the Minimum Safe Altitude Alarm (MSAW) at the remote tower site.

The Remote Display Buffer Memory is capable of refreshing either the Tower Cab Digital Display(TCDD) or the A/N modification to the Tower Cab Brite Display. Each display has defined for it performance criteria which constitutes its display model. The display model for the TCDD requires that the display present a display load which requires about 2000 words at the rate of 55 Hz. Therefore, the TCDD must have the total 2000 words available during the 18 milliseconds of refresh time, furthermore, the display must not experience a delay between its output data request and receiving of a data word. The RDBM does not prevent the TCDD from meeting its performance criteria for its display model. First, since the time required to present 2000 words of the display mode to the display required 3.2 microseconds per word or a total of 6.4 milliseconds. The entire model can be generated to the display within the limits of its refresh time (i.e., within 18 milliseconds). Secondly, the typical time for the display to write a word on the display is about 8 microseconds. While the display is writing the word on the display the RDBM can present in excess of 2 words of data to the display. The A/N modification to the Tower Cab Brite Display model requires that about 557 words of data to be presented on the display at the rate of 24 Hz. Therefore, the total 557 words must be made available to the display in a time frame of about 41.6 milliseconds. The RDBM does not prevent this display model from being met since the RDBM can present all 557 words to the display in about 1.8 milliseconds. The time to write a word on the display is typically about twice the time required to receive another data word from the RDBM.

The amount of time required to accept data from the serial adapter and present it to the display is the throughput data time. The throughput data time for the data is typically less than 33 milliseconds.

The input section of the Tower Cab Digital Display (TCDD) generates three data words per refresh cycle to transmit positional (track ball) and keyboard entry data for the two data entry sets. The TCDD also generates a parity error interrupt word immediately upon detection of a parity error in a refresh data word. These words are buffered and processed by the RDBM and the required trackball cursor symbol or keyboard preview are entry data words are updated by the RDBM. Data entry words which do not contain new data, i.e., idle codes, disconnect codes or no change words are filtered out of the input data messages to the ARTS III site. All valid input data messages are converted to serial format prior to transmission to the ARTS III site. The addition of the RDBM to the ARTS system also provides a device which can be read into and read back for on-line confidence checks of the communication link.

The RDBM is capable of executing diagnostic programs stored in ROM memory for self test of

the RDBM and diagnostic testing of the tower cab display subsystem. The enable execution of the diagnostic programs may be selected by the processor at the host ARTS III site or from the RDBM maintenance panel.

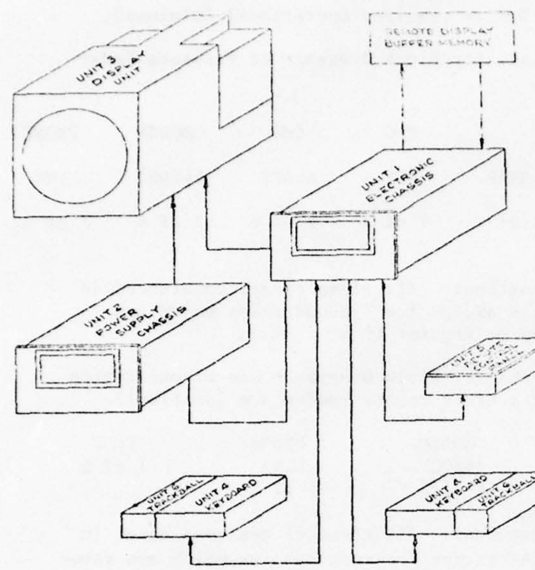

FIGURE 10, TCDD SUBSYSTEM MAJOR ELEMENTS

Tower Cab Digital Display (TCDD) - The TCDD is a computer-driven display subsystem incorporating all elements necessary for stand alone operation in an automated radar tower cab environment. It features a random-positioned, high-speed display monitor that produces high-brightness imagery of both textual and graphical data. Data entry devices, including two keyboard and trackball modules and one control panel, permitting easy operator interaction with the system computer are also included.

The overall content and operation of the TCDD is best conveyed by the simplified block diagrams Figure 10 and 11. The blocks represent the prinicpal functional elements utilized. They are arranged to show their physical grouping and the primary information flow between them. Also, the blocks are representative of the circuit implementation employed. In most cases, functions are realized by one or two plug-in circuit card assemblies.

As a computer interactive subsystem, the TCDD provides ARTS III compatible line receivers and drivers, and separate fully buffered input/output channels.

The format generator then decodes, transfers, and sequences the digital data through four function generators under its command.

The high speed D/A position generator

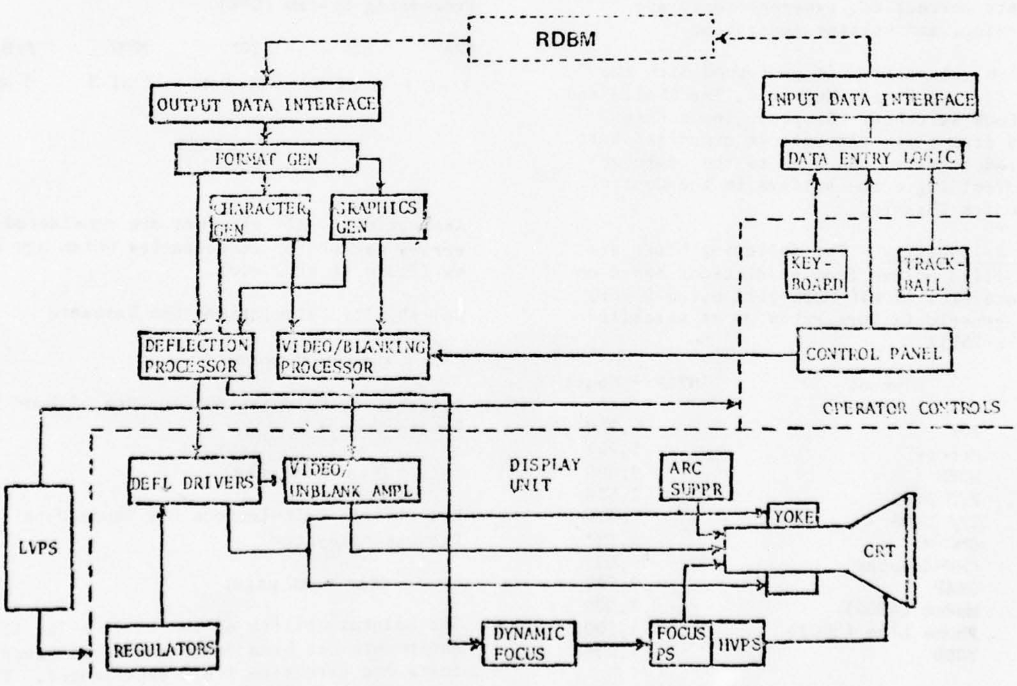

FIGURE 11, TCDD SUBSYSTEM BLOCK DIAGRAM

establishes base X-Y position and also provides character-to-character spacing and line indexing.

The stroke-type character generator responds to six-bit code words and "GO" commands with incremental deflections, video, and an "END" signal back to the format generator. The average character writing time is about 4 microseconds.

The vector generator responds to end-point data words as well as leader orientation and length. At the "GO" command, it produces constant-velocity deflection increments, video, and a "Complete" signal.

The circle generator receives radius and arc start/stop data, then produces sine/cosine reference waveforms for use by the vector generator output section under "GO" and "Complete" time control.

The outputs of these function generators are then combined with necessary correction waveforms in the deflection and video processor modules which produce the final composite drive signals for the Display Monitor Unit.

In the Monitor, precision deflection-current drivers produce accurate, stable motion of the CRT beam. Simultaneously, a very wideband video driver modulates this beam to create the crisp, bright traces on the display. Supportive functions include dynamic focus, flat-rate correction, sweep-protect, arc suppression, and voltage generation.

Operation interaction is performed with the Remote Control Panel, Keyboard, Trackball, and Quick Look Switches. Computer input data derived from these elements is organized into specified formats, and sent to the computer via control logic and buffers in the Control Electronics Chassis.

System Reliability - The following MTBFs are as specified or are from predictions based on the procedures of MIL-HDBK-217A using Sperry Univac generic failure rates or as specified in FAA-E-2591A.

Element	MTBF - Hours
IOP	6,250
Memory	5,943
MDBM	9,000
F/D DEDS	2,516
T/S DEDS	2,516
CMC-MUX	6,357
CMC-Adapter	56,623
SRAP	2,987
Modem (4800)	7,000
Phone Line (3002)	1,200
TCDD	1,736

Redundant calculation use Einhornes formula for active redundant units with repair capability

$$MUT = MTBF \left(\frac{MTBF}{MTTR}\right)^{N-R} \frac{1}{R\left(\frac{N!}{R!(N-R)!}\right)}$$

N - Number available
R - Number required operational (minimum)

Reliability Block Diagrams of Sarasota Radar Site

	CMC	CMC	MODEM	PHONE
SRAP	MUX	ADAPT	(4800)	LINE
1 of 2	1 of 2	2 of 8	2 of 4	2 of 4

Assumptions: All elements are considered in series except for redundancies which are shown by figures (1 of 2 etc).

Reliability Block Diagram - One of our remote towers (four remote towers are identical).

MODEM 4800	PHONE LINE	TCDD
1 of 2	1 of 2	1 of 2

Assumptions: All elements are considered in series except for redundancies which are shown by figures (1 of 2 etc).

Reliability Block Diagram - Tampa Data Processing System (DPS).

SRAP	MEM	IOP	MDBM	F/D DEDS
1 of 2	7 of 9	2 of 4	2 of 3	1 of 3

T/S DEDS
3 of 7

Assumptions: All elements are considered in series except for redundancies which are shown by figure (1 of 2 etc).

Reliability Calculations for Sarasota

(See next page)

Reliability Calculations for One of Four Remote Towers

(See next page)

Reliability Calculations for Tampa Data Processing System

(See next page)

The maintainability of the basic ARTSs III equipments has been demonstrated in several tests and extensive field experiences. The ARTS IIIA remoting system makes use of both proven ARTS III equipments and new system developments. The new devices basically

Reliability Calculations for Sarasota

UNIT	QUALITY	MTBF ea	MUT	FR
SRAP	1 of 2	2,987	2.68×10^{7}	3.73×10^{-8}
CMC-MUX	1 of 2	6,357	4.04×10^{7}	2.47×10^{-8}
CMC-Adpt.	2 of 8	56,623	3.172×10^{36}	3.15×10^{-37}
Modem (4800)	2 of 4	7,000	11.4×10^{10}	8.77×10^{-12}
Phone Line	2 of 4	1,200	5.76×10^{8}	17.36×10^{-10}
			Total	6.201736×10^{-8}
			MTBF	16,124,517 hrs.

Reliability Calculations for One of Four Remote Towers

UNIT	QUALITY	MTBF ea	MUT	FR
Modem (4800	1 of 2	7,000	4.9×10^{7}	2.04×10^{-8}
Phone Line	1 of 2	1,200	1.44×10^{6}	6.94×10^{-7}
TCDD	1 of 2	1,736	3.01×10^{6}	3.32×10^{7}
			Total	10.464×10^{-7}
			MTBF	955,657 hrs.

Reliability Calculations for Tampa Data Processing System.

UNIT	QUALITY	MTBF ea	MUT	FR
SRAP	1 of 2	2,987	2.68×10^{7}	3.73×10^{-8}
MEM	7 of 9	5,943	3.33×10^{9}	3.003×10^{-10}
IOP	2 of 4	6,250	8.13×10^{10}	1.23×10^{-11}
F/D DEDS	1 of 3	2,516	2.12×10^{10}	4.71×10^{-11}
T/S DEDS	3 of 7	2,516	7.68×10^{15}	1.302×10^{-16}
MDBM	2 of 3	9,000	27.0×10^{6}	3.7×10^{-8}
			TOTAL	7.433003×10^{-8}
			MTBF	13,453,512 hrs.

include the SRAP, RDBM, TCDD and CMC modules. These devices have had their designs influenced greatly by maintainability considerations. The SRAP, RDBM and CMC both employ microprocessors in their design and built-in test hardware and software. The MTTR goals for each of these two devices is 10 minutes. The SRAP, CMC, Modems, and Phone Lines make up the radar remoting link to Sarasota. Since dual SRAP units are provided and the Modem/Phone Lines problems can be quickly isolated through the use of patch panels, fault isolation to a specific element should be fast and definite. The same basic redundancy exists at the remote tower sites with dual phone lines, modems, RDBMs and TCDDs. This, in conjunction with the excellent MTTRs of the individual system elements and system redundancy, should provide excellent system maintainability roughly equal

to or better than the basic ARTS III system which was demonstrated at 22 minutes MTTR.

The MTRR estimated for all the individual elements are all 1/2 hour, except the SRAP and CMC which are 10 minutes.

System Software - The system software consists of four distinct types. They are 1) Operational, 2) On-Call, 3) Off-line, and 4) Recovery. The Operational Software consists of 1) Executive, 2) Task, and 3) Data Base elements. All portions of the Operational Software will be resident in computer memory. The operational software is responsible for meeting the real-time requirements of the system. The On-Call Software consists of software tasks or modules which will be loaded from the disc into an area of operational computer memory reserved for this purpose. One and only one On-Call module will be resident at any given time. The On-Call capability is used for modules which require use of operational peripherals or access to the operational program but are not required as part of the operational program. The following On-Call modules will be provided:

1) Data Transfer (disc to tape, tape to disc, disc to disc)
2) Beacon Radar On-Line Performance Monitor (BROPM)
3) Enhanced Target Generator (target generator portion)
4) Print on MSP from magnetic tape in HSP format
5) Display Alignment Patterns

Off-Line Software is the collection of support, utility, and diagnostic software which operates independent of the operational program, except that the off-line and operational program will share the disc subsystem.

Off-Line software may use the disc but shall not obtain access to the disc via a demand control. Recovery Software is executed following a scatter interrup which may be initiated manually at the Reconfiguration and Fault Detection Unit (RFDU) or automatically after a failure within the computer system. It is executed prior to execution of the reloaded operational program. Recovery software consists of two parts, namely: 1) Non Destructive Read Only Memory (NDRO), and 2) Recovery Module. The NDRO module is contained in read only memory within each processor. The NDRO module will determine the initial processor and memory resources and load the recovery module from disc to the lowest operational numbered original memory unit. The recovery module consists of processor and memory diagnostics. These diagnostics refine the list of initial resources. After final evaluation is complete, the recovery module loads the operational program consistent with the available resources.

Operational Software - The software function is divided into eight major areas:

1) Multiprocessing Executive (MPE)
2) SRAP Input Processing (Local and Remote)
3) Tracking
4) Display Output Processing (including Remote TCDD)
5) Keyboard Input Processing (including remote TCDD)
6) Interfacility Flight Plan Processing
7) Minimum Safe Altitude Warning (MSAW)
8) Continuous Data Recording

The MPE provides overall control of the operational program.

The SRAP Input processing accepts declared targets and passes them to tracking.

The tracking function performs a scan-to-scan correlation of the declaried targets to provide positional and informational data for display output processing. The positional data is the XY position in radar coordinates. The informational data is the ground speed and altitude, which is contained in the Full data block.

The tracking function operates separately on the two subsystems. It has an automatic track start and acquisition feature. It maintains track files on all declared tracks.

The display output function gathers data from the tracking function, keyboard input function, MSAW function, and the interfacility processing and prepares it for output to the displays. This function will output to the DEDS through an MDBM and to the TCDD via the CMC and RDBM.

The keyboard input processing function accepts data from the DEDS and TCDD keyboards and performs the desired function.

The interfacility flight plan processing communicates with the ARTCC computer. This function accepts flight plan information and passes this data to the tracking and display output functions.

The MSAW function includes altitude tracking and general terrain and approach path warning logic.

The continuous data recording is the control and logical recording of ATC data on the disc.

In event of a hardware failure in the data processing elements the system has first level backup, and second level backup programs to match the available hardware resources. Reduced levels are attained by reducing the data base and by eliminating some tasks. To simplify the assembling and building of operational systems, backup levels are created by eliminating entire tasks while retaining the full capability of the remaining tasks. This method of reduction provides a manageable number of task configurations.

The reduction from one level to the next shall be accomplished by the Recovery Module described below. Critical data previously recorded is used to establish a data base for the reduced version.

Full Dual Radar Beacon Tracking Level (RBTL) Operational Functions - This version processes all ARTS IIIA functions for both the Tampa and Sarasota systems. It operates in a 3 IOP X 9 MM configuration. Since the Tampa system is a 4 IOP x 10 MM version it is failsafe for 1 IOP or 1 MM failure. Total track capacity is 600 radar/beacon tracks, consisting of 400 associated and 200 unassociated tracks.

First Level Dual Backup Operational Function - This version processes both Tampa and Sarasota system functions and operates in a 3 IOP X 8 MM configuration. Total track capacity is 600 tracks, consisting of 480 associated and the remainder tabular. This version is identical to the full up with the exception of on call programs, bulkstore, two maintenance DEDS, 1 training DEDS and 3 TCDDs removed.

Second Level Dual Backup Operational Function - This version processes only the Tampa system functions and operates in a 2 IOP X 6 MM configuration. Total track capacity is 300 tracks, consisting of 150 associated and the remainder tabular. This version has the following functions removed.

- o All Sarasota System Functions
- o All Remote Tower Display Functions
- o Debug Aids
- o Auto Offset
- o Continuous Data Recording
- o Critical Data Recording
- o Bulk Store Flight Plan Processing
- o On-Call Control and Tasks

Operational Software Components - The operational software consists of the executive tasks, and data base. The executive modules, tasks, and data base elements are assembled independent of one another. The "Builder" program loads and links these components producing an operational program in bootstrap loadable format. The Builder Utility Program (BUP) will take various operational subprograms, the recovery module, on-call modules, off-line programs and produce a Recovery System Library (RSL) on the disc. The RSL contains directories describing the location of these programs.

Executive - The Failsafe/Failsoft Multiprocessor Executive program (MPE) provides the overall control of the Multiprocessor Data Processing Subsystem (MDPS) by handling the scheduling and dispatching of operational tasks. Interface with the tasks is maintained through the scheduler and EXIT from the tasks, and other Executive Service Requests (ESRs) as required. Figure 12 is a block diagram showing the executive program overview. Tasks have many operating needs, consisting, as a

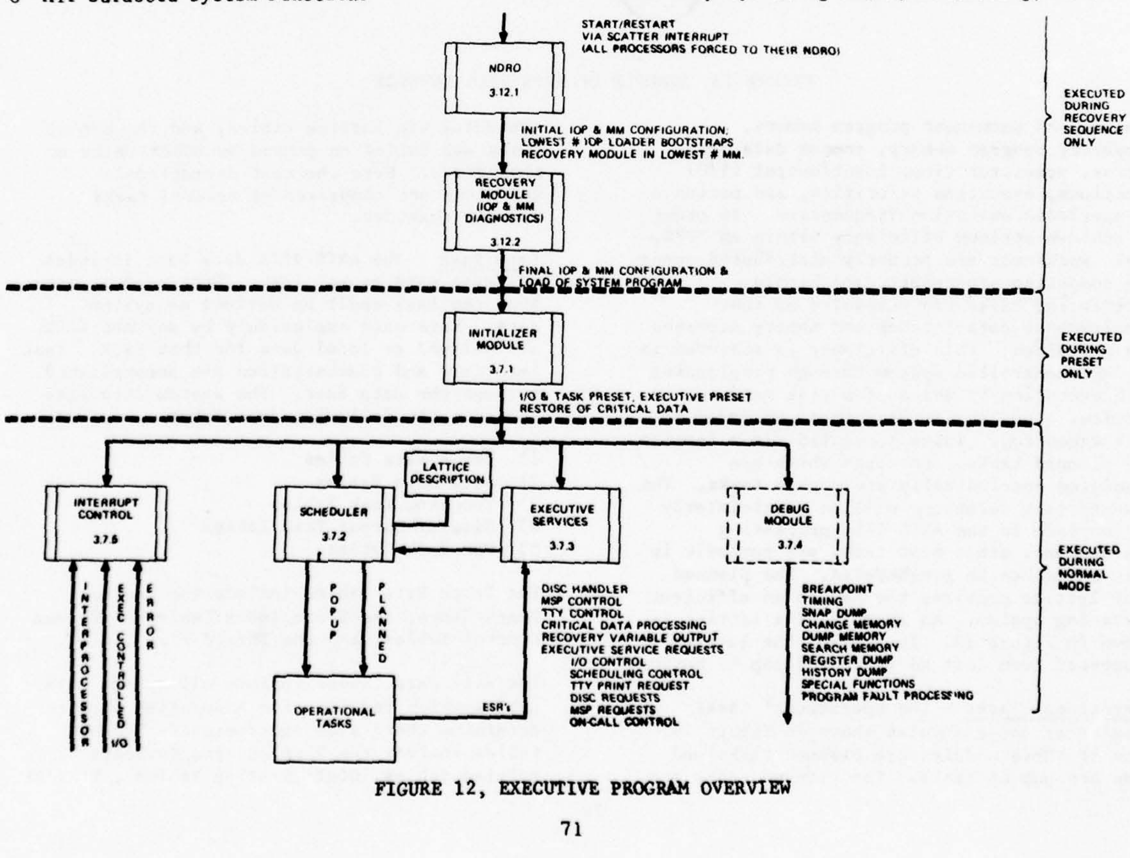

FIGURE 12, EXECUTIVE PROGRAM OVERVIEW

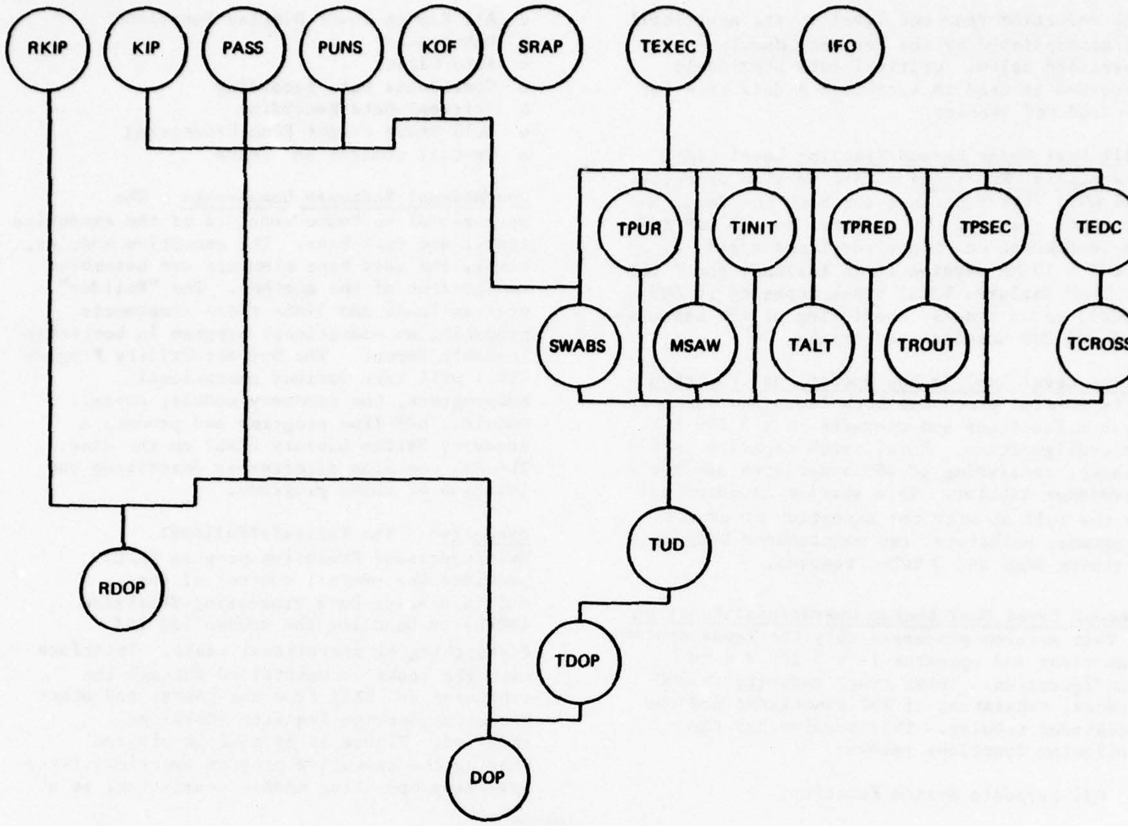

FIGURE 13, EXAMPLE OF ARTS IIIA LATTICE

minimum, of permanent program memory, temporary program memory, common data base access, processor time, input/output (I/O) functions, execution priorities, and periodic or aperiodic execution frequencies. In order to achieve optimum efficiency within an MDPS, task workloads are properly distributed among the competing processors, and highly interfacing tasks are scheduled so that simultaneous data fetches and memory accesses are minimized. This efficiency is achieved in the MPE controlled system through preplanning task execution by means of a task network, or lattice. The lattice describes the order of task execution. Tasks scheduled via a lattice are planned tasks, and tasks which are scheduled aperiodically are pop-up tasks. The planned task technique will be particiularly appropriate to the ARTS IIIA processing environment, since most tasks are periodic in nature and can be presheduled. The planned task lattice provides the key to an efficient operating system. An example of a lattice is shown in Figure 13. In general the lattice is processed from left to right and top to bottom.

Operational Tasks - The operational tasks consist of those modules shown in Figure 14. Some of those modules are planned tasks and some are pop-up tasks. The planned tasks are scheduled via lattice tables, and the pop-up tasks are called on demand by other tasks or themselves. Note the most operational functions are comprised of several tasks working together.

Data Base - The ARTS IIIA data base includes all data used by any task. Data used by more than one task shall be defined as system data. Data used exclusively by any one task are defined as local data for that task. Task interface and communication are accomplished through the data base. The system data base includes the following data types:

1) Track Data Tables
2) Site Data Tables
3) Tracking Task Tables
4) Display Output Task Tables
5) CDR Task Tables

The Track Data Tables include the Central Track Store, the Track Index Table, the Thread Control Tables, and the Thread Flag Table .

The site data tables include all system data tables which require site adaptation data to determine their size and content. These tables include the Display and Keyboard related tables, Configuration Tables , VFR/IFR

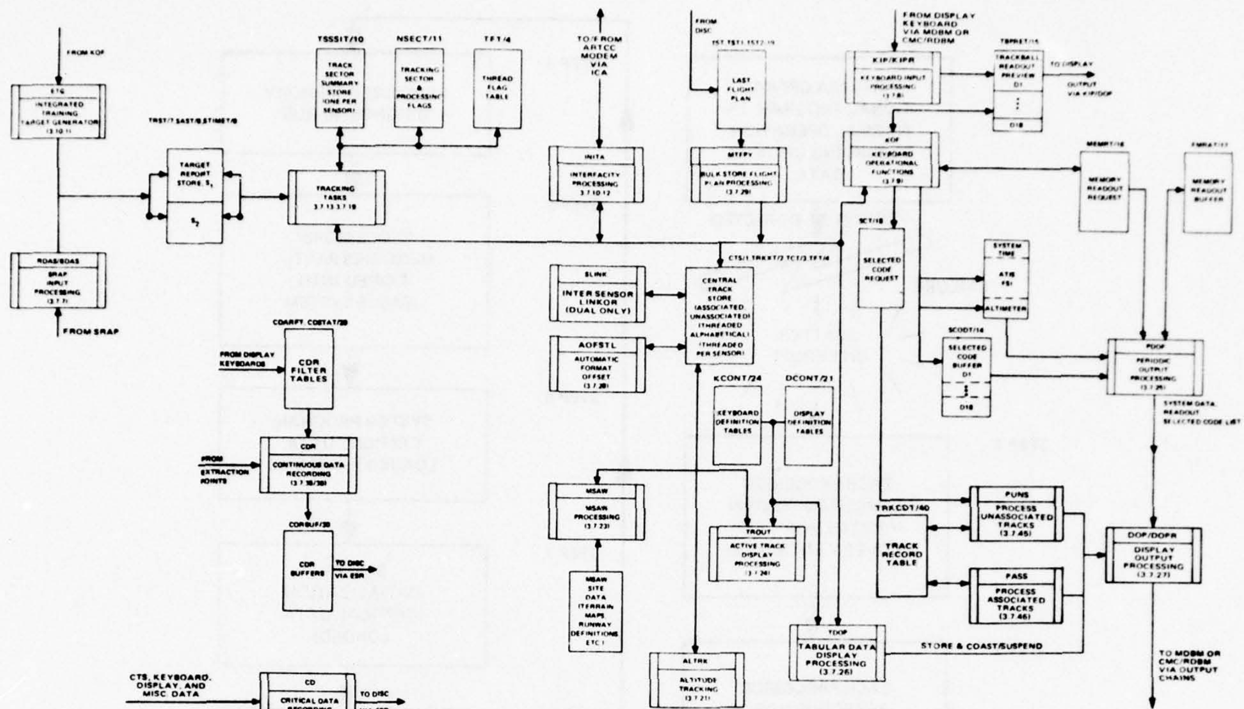

FIGURE 14, OPERATIONAL TEST OVERVIEW

Tables and Fix Character Table.

The tracking task tables include data necessary for all tracking tasks. These tables include the Target Report Stores, the Target Report Sector Access Store, the Target Report Sector Time Store, the Track Sector Summary Table and the New Sector Referencing Table.

The display output task tables include the tables necessary to effect a "changed data only" display output function. These tables include the MDBM Input Chain Table, the MDBM Keyboard Input Buffers, the Keyboard Input Buffer Index Table, the System Display Buffers, the Memory Readout Request Table, the Memory Readout Buffer, the Selected Code Table, and the Track Record Table.

The CDR task tables include filters and buffer areas necessary to accomplish the CDR function. These tables include the CDR Filter table and the CDR Buffers.

Local Data Bases - Local data bases are defined for each task. This data includes local working storage, flags, and tables. Also included, shall be site adapted data used exclusively by a particular task (i.e., MSAW maps and tables).

Memory Sequence - The recovery sequence is initiated by a scatter interrupt which may be caused by a hardware error, a software detected error, or may be manually initiated at the RFDU. Recovery consists of two distinct elements; an NDRO program, and a recovery module which is loaded into main memory. This software allows the operable resources to recover from a detected failure.

Scatter interrupts may be caused by any of the following errors;
1) Power Interrupt
2) Memory Lockout
3) Memory Parity
4) Illegal Address
5) Program Fault
6) Time Away from Executive Error
7) Time in Executive Error
8) Real time Clock error
9) Single Point Start Button.

Figure 15 is a diagram of the Recovery Sequence. A discussion of the sequence follows:

Step 1 - Each processor in the system is forced into its own (processor unique) NDRO memory upon receipt of a scatter interrupt. All other computation and I/O are terminated at this time.

Step 2 - A limited processor diagnostic and memory test is run in each processor. The

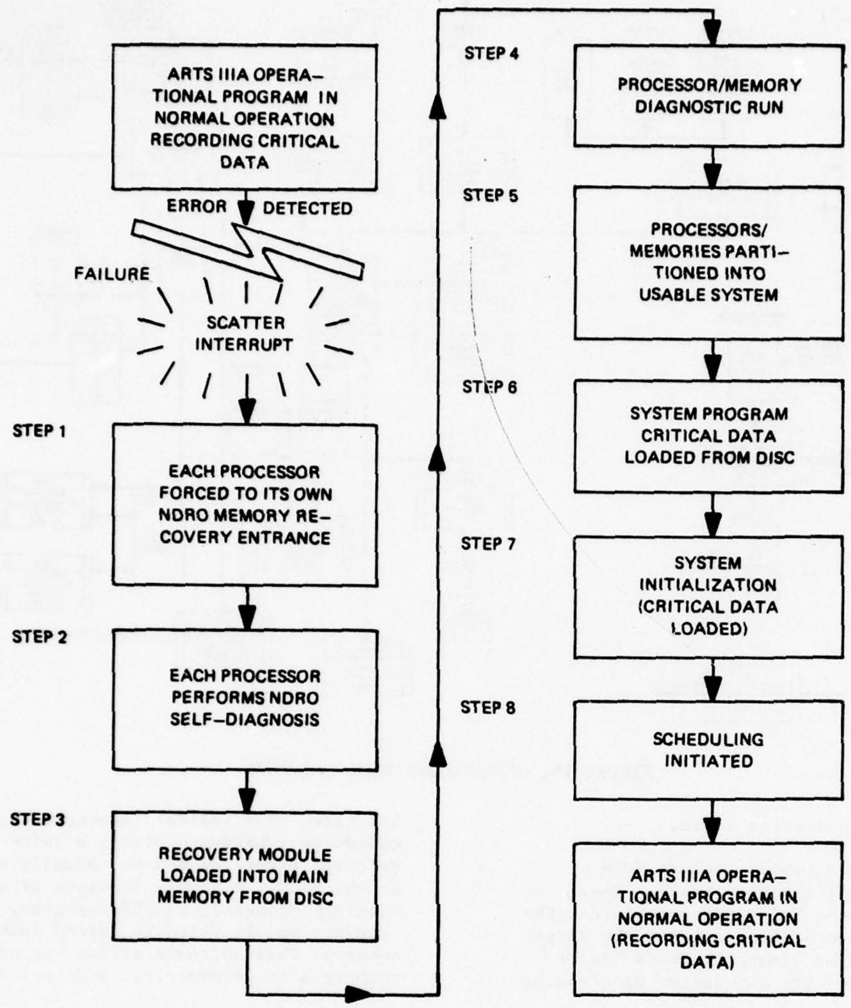

FIGURE 15, RECOVERY SEQUENCE

processor diagnostic is limited to those instructions necessary to complete the processor testing, memory testing, and program loading. The memory test performs memory module access tests but not individual word tests. Only processors passing the test and memory modules which test good to all of the processors are retained in the system for step 3.

Step 3 - The Recovery Module is loaded into the lowest numbered operational memory module (relative memory 0) remaining after step 2, by the lowest numbered operational processor cabled to the load device (disc or IMT). Following a successful load, all processors begin execution of the Recovery Module in relative memory 0.

Step 4 - The first test in the Recovery Module is the execution of the IOP diagnostic. Following the diagnostic, all processors are tested for interprocessor interrupt communications. The final test of the Recovery Module is a memory test in which each word of each memory is tested with two discrete bit patterns.

Step 5 - Following the completion of the testing, the usable system is determined by including all processors which have passed the tests and all memories which test good from all processors involved.

Step 6 - The system program directory is then read from the disc and a program level selected which will run with the available resources. This program level is then loaded.

Step 7 - Once the program is loaded, initialization proceeds on the lowest numbered

operational processor. Exeuctive initialization is done first, followed by operation program module initialization. Critical data is loaded from the disc during intialization and used as required to effect a complete recovery.

Step 8 - When initialization has been completed, normal multiprocessing scheduling is initiated and the operational program resumes normal operation

Timing and Sizing - Timing studies done by UNIVAC show that the system processing load is 2.54 processors. Therefore, 3 IOPs can carry the load with some margin and 4 IOPs allow for a failsafe configuration. The biggest users of processor time are: the executive (.24), tracking (.80), display output (.60) and remote display output (.20). The figures in parenthesis are fractional parts of the total processing capability of a single IOP (i.e., tracking uses 80 percent of one IOP). Program size is about 140K (30-bit words) with about equal division between data base and program instructions. The larger program modules are: executive (4K), keyboard functions (8K), tracking (4K), on-call programs (6K) and common subroutines (5K). The biggest data base tables are: central track store (30K), MDBM buffers (6K), track record tables (4K), critical data buffers (5K) and RDBM buffers (5K).

CONCLUSION

This FAA project is another major step forward in the evolutionary growth to a full digital terminal operation. Expected benefits are: wider use of available radar information, fewer siting restrictions for terminal radars, improved ATC coordination between IFR rooms and remote towers and lower communication costs due to the substitution of 4800 b/s digital circuits for the more expensive radar microwave links (RML) now used to transmit radar information

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ASDE-3

A NEW AIRPORT SURFACE DETECTION EQUIPMENT SURVEILLANCE RADAR

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BIOGRAPHY

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Mr. Bloom received his degree in Electronic Engineering from Manhattan College in 1957 and has completed extended electronic graduate studies at the University of Florida. He was a Field Service Engineer on avionics at Sevromechanisms, Inc. in 1951. Subsequently, he worked on the electronic design, system design and launch support activities for the missile guidance systems at Honeywell Aero, Florida. He than became a System's Analysis group supervisor for guidance and navigation at Honeywell Aero in 1967. His next assignment was as a System Development Head at Dynamics Research Corporation for minicomputer development and digital technology systems development until 1971. He is currently a Project Engineer at TSC and is responsible for the specification and development of the ASDE-3 radar.

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ABSTRACT

The key factor necessary for Airport Surface Traffic Control is adequate surveillance capability for the Control Tower under all operating weather conditions. ASDE is the solution for providing the surveillance capability under poor visibility conditions at most airports when the primary visual surveillance mode through the Control Tower's windows cannot be used. A new airport surface surveillance radar, ASDE-3, is currently being developed by the Federal Aviation Administration (FAA) to satisfy the Control Tower requirements.

The paper develops the critical surveillance and operational design requirements that the new ASDE-3 radar has to meet. Having done so, the major equipment design requirements are then treated in considerable detail. Principal among these are the selection of 16 GHz in lieu of 24 GHz used in the present ASDE-2 and a unique antenna design to obtain maximum weather performance for a given antenna enclosure size constrained by wind-induced overturning moment considerations. The net result of the antenna design is an integral antenna/rotodome wherein the antenna has variable focus and cosecant elevation beam-shaping. Another significant departure from the ASDE-2 is the use of a multiple-step frequency-agile traveling wave tube transmitter. The paper also discusses the expected benefits, namely; (a) precipitation-clutter pulse-to-pulse decorrelation, (b) improvement in target-imaging, and (c) elimination of multiple-time-around targets.

The ASDE-3 will have a weather adaptive receiver gain control which compensates for changes in precipitation-attenuation path loss with airport surface-mounted reflectors of 10 m^2 radar cross section providing the reference level. The next subsystem discussed is the Display Enhancement Unit which provides the digitally generated map of the airport and separates areas of interest to the controller from suppressed areas.

Finally, the schedule indicates that Test and Evaluation at NAFEC should be completed by the summer of 1979 thereby allowing for a FY-80 production contract.

AIRPORT SURFACE TRAFFIC CONTROL SURVEILLANCE REQUIREMENTS

Airport Surface Traffic Control System

The Airport Surface Traffic Control (ASTC) System is defined as that system (people, procedures, and equipment) which is concerned with the movement of:

a. Arriving aircraft through the phases of final approach, landing, and taxiing to the passenger terminal (or cargo or general aviation area, if applicable).

b. Departing aircraft through the phases of pushback from the passenger terminal, taxiing to the departure runway, takeoff, and initial climb.

c. Aircraft in transit between sites at the airport; e.g., from passenger terminal to cargo or maintenance area.

d. Service or emergency vehicles; e.g., snow plows or fire engines, operating on the airport taxiways and/or runways.

The ASTC System manages the flow of vehicle movement within its jurisdiction so as to achieve the best balance for:

1) Maximizing safety and quality of service.

2) Minimizing aircraft delays and fuel use.

3) Minimizing air pollution and noise.

4) Minimizing costs incurred by airport operators, users, and participating local, state, and Federal government agencies.

Airport Surface Traffic Control is exercised from the Control Tower Cab that is situated above the airport to provide good visual coverage. In general, two control positions are involved, Ground Control for taxiway network control and Local Control for

runway management including landing clearance, takeoff clearance, and runway crossing clearance.

Surveillance, the Key Factor

Surveillance is the process whereby Ground and Local Controls acquire information on the position and identity of vehicles under their jurisdiction. The Ground Controller uses visual observation, through the windows of the tower cab, as his primary means of surveillance. The Local Controller uses visual observation and the Airport Surveillance Radar (ASR) as his primary surveillance media. The ASR, which provides a radar-derived display of the positions and associated identities of airborne aircraft in the vicinity of the airport, is used to monitor aircraft on final approach or initial climb. Airport Surface Detection Equipment (ASDE-2), a high resolution, ground-mapping radar is available at 12 airports. The function of an ASDE is to provide a display of airport surface traffic activity for use by the Ground and Local Controllers during conditions of reduced visibility due to weather or darkness. (A typical ASDE-2 display presentation is shown in Fig. 1.)

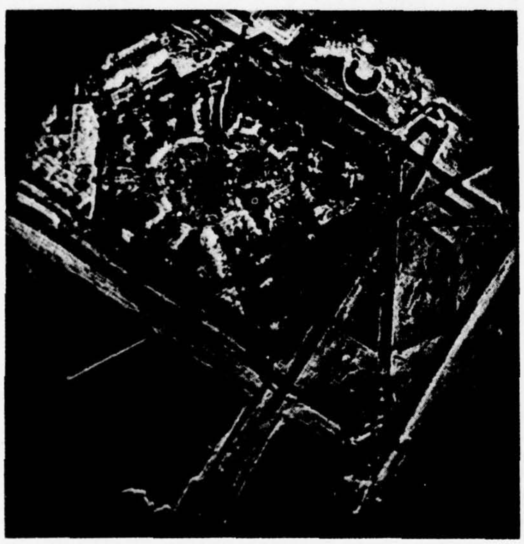

Fig. 1. ASDE-2 display at John F. Kennedy Airport.

The Transportation Systems Center (TSC) has conducted extensive analyses of the ASTC System and has concluded that its principal problems, both today and through the 1980's, relate to surveillance under poor visibility conditions. Although other elements of the system such as the communication and control functions do exhibit problems, these problems appear to be induced by the deficiencies of the surveillance system and do not warrant extensive non-surveillance-related system developments such as automation of the Control or Communications functions.

ASDF, the Surveillance Solution at Most Airports

Without an ASDE, the Controllers experience difficulties during poor visibility conditions, and must rely on pilot position reports via VHF radio. For the Local Controller, the principal problem is the loss of timing information regarding runway operations. In general, the distribution of arrival traffic is determined by the Approach Controller in the IFR room. The Local Controller's problem then is to fit his departure traffic into the release opportunities afforded by the distribution of arrival traffic. This is particularly important where a single runway is used for mixed arrival and departure traffic or where the arrival and departure runways intersect. In the absence of an ASDE, poor visibility forces Local Control to rely on imprecise pilot-position reports. This results in loss of runway capacity of, for example, approximately 25 percent for the single mixed runway case. The plan view ASDE display provides position and timing information on runway traffic and on arrival and departure aircraft up to an altitude of about 150 feet. With an ASDE, therefore, runway capacity in poor visibility can be restored to within about 5 percent of the good visibility capacity for the single mixed runway case. Lack of identity information on the ASDE display has little significance for Local Control since his traffic is ordered and sequential, allowing ready correlation between the ASDE position information and flight strip identity.

For Ground Control, timing information is not critical but information on position and identification is. Of the 50 percent or so capacity loss experienced by Ground Control because of poor visibility, only about a third of this lost capacity is restored by use of an ASDE radar. The principal problem is the correlation

of radar position information with vehicle identification. The Ground Controller's traffic is not well ordered, and significant VHF radio traffic is required during poor visibility conditions to maintain position/identity correlation on the ASDE display. This VHF traffic tends to drive the Ground Controller's radio channel into saturation and substantially reduce the controller's capacity.

Fortunately, except for exceptional circumstance, it is the Local Control (runway capacity), and not Ground Control capacity, which limits airport traffic-handling capability. Thus, an ASDE-equipped Ground Controller can match the capacity of an ASDE-equipped Local Controller under poor visibility, despite loss of the Ground Controller's capacity relative to his good weather performance. The exception to this rule is an airport which operates more than one Category II runway in poor visibility with a net arrival/departure rate exceeding 65 operations per hour. For those few airports (approximately six U.S. airports by 1985) something beyond ASDE is required to provide position and identity. Such a system (called TAGS) is under development by TSC and has been reported previously.[1] For most airports (30 to 40), which need poor visibility surveillance augmentation, ASDE provides the required capability at considerably less cost than TAGS.

Having discussed the role of an ASDE in control tower operations, let us now consider what is required of the ASDE if it is to fulfill that role successfully.

ASDE DESIGN CONSIDERATIONS

Weather Penetration, a Primary Requirement

The role of an ASDE, as discussed previously, is to provide the alternative means of airport surveillance for the Control Tower when visibility through the Tower windows is restricted. The most persistent complaint of Controllers regarding ASDE-2 has been that it works best when they do not need it, and works worst when they need it the most. Since visibility restrictions are caused by weather, weather penetration is a primary ASDE requirement. The ASDE-3 weather penetration (rainfall rate) requirement is based on several factors including climatic data for candidate airports, visibility effects of weather, the operational availability needed for reliable surveillance, and the performance which can reasonably be achieved by an ASDE radar.

Over 30 airports have been identified as ASDE-3 candidates using the FAA ASDE establishment criteria. Available climatic data for 21 airports slated to receive ASDE-3 were analyzed to determine the rainfall rate capability required at each airport to assure ASDE surveillance availability for the Control Tower 95 percent of the time when visibility is under 1 mile.

Fig. 2 shows the rainfall rate capability required for each site plotted against the maximum range required at each site. The data plotted establish the limits of weather penetration required for ASDE-3 as a function of range. Also plotted on the same figure is the result of a radar detection analysis of a 16-GHz ASDE-3 using reasonable and achieveable parameters. A constant-detection criterion was assumed, using a probability of detection (P_d) of 0.9 and a probability of false alarm (P_{fa}) of 10^{-6} for a non-fluctuating 3 m^2 target, without integration. Note that the ASDE-3 radar as plotted satisfies all sites except 2; i.e., Dallas Fort Worth (DFW) and New Orleans (MSY), which would be satisified if 90- instead of 95-percent availability were used. Thus, an ASDE-3 radar with characteristics similar to those assumed adequately satisfies the weather penetration requirements.

Achieving weather penetration is an important ASDE design consideration; however, equally important is the presentation of a good surveillance picture on the Control Tower display.

Providing the Surveillance Information on the ASDE Control Tower Display

The Control Tower, to perform its traffic management functions, requires the ASDE display to provide target-imaging and target-to-target resolution to:

a. Discern any active runway traffic.

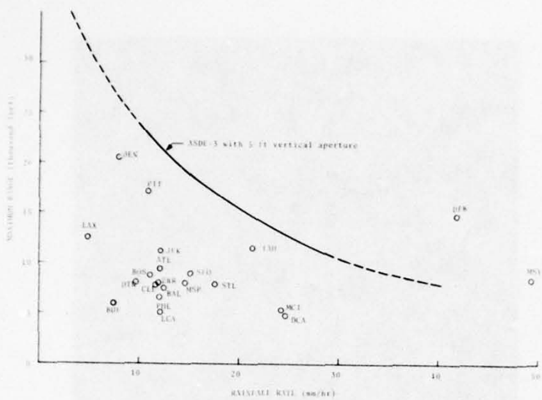

Fig. 2. Rainfall rate requirement for 21 U.S. airports.

b. Discern the position of aircraft/vehicle relative to runway and taxiway intersections.

c. Track traffic on runways and taxiways, and discriminate closely spaced targets.

d. Recognize aircraft by shape and size.

e. Recognize airport runway and taxiway background.

These functions require a radar resolution about 15 to 20 feet in range and 0.25 degree in azimuth, and an antenna rotation rate of once per second. The rotation rate is based on long experience with ASDE-2, and on simulation studies done by TSC.[2]

The ASDE-3 will use the ASDE NU BRITE display system developed by TSC for FAA and built by ITT Fort Wayne. This TV-vidicon scan-conversion display system, based on the Airport Surveillance Radar (ASR) BRITE technology, was specifically developed for the ASDE application, and is currently installed and successfully operating at three ASDE-2 sites. The NU BRITE uses a high-brightness, high-contrast TV compatible with Control Tower ambient light conditions, and has a 15-foot resolution capability on the 6000 feet per diameter scale.

Another important factor related to the presentation of surface surveillance information to the Control Tower is the ability of the display to allow the controller quickly to acquire and track targets of interest. ASDE radar returns provide near photographic-quality data from the entire airport surface display, including grass areas, buildings, and other surface features outside of the traffic movement areas of interest. Displaying extraneous information from outside of the taxiway/runway movement areas limits the ability of the display to present clearly the surveillance information normally needed. (Surveillance of other parts of the airport outside of the movement areas may be necessary under certain emergency conditions.) To provide the best possible presentation of the taxiway/runway movement areas, ASDE-3 will include a unit similar to a mapper, called a Display Enhancement Unit (DEU). The DEU, as illustrated in Fig. 3, allows the controller proportionally to adjust the contrast between movement and non-movement areas, and also the intensity of map lines defining the movement areas.

Experiments conducted by TSC at Dallas Love Field, Texas, using a DEU breadboard developed by TI, indicated a 25- to 40-percent improvement in "quick look" aircraft-detection capability when compared with a normal ASDE presentation.

Having considered weather penetration and proving the surveillance information needed for the Control Tower operation, let us address airport site factors such as the tower for antenna-mounting, antenna-siting, and radar coverage.

Airport Site Factors

Since the ASDE is to provide surface surveillance for the Tower Controllers, the radar must be located in a position providing line of sight to all parts of the airport surface. For most airports, the ideal location would be the Control Tower roof. However, at many airports, the Control Tower structure is very limited in the ability to support additional loads on the roof. Consequently, the weight and size of the ASDE-3 antenna/radome

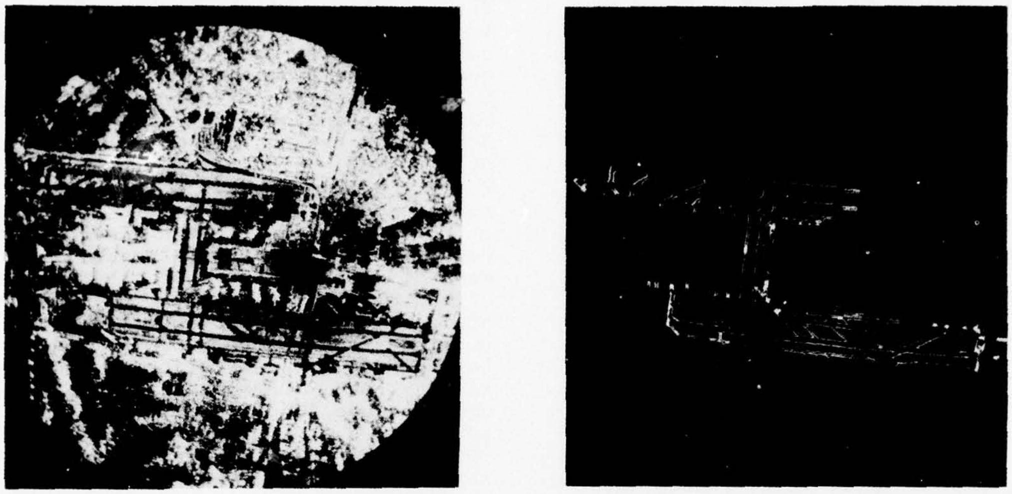

Fig. 3. Los Angeles Airport ASDE without and with a display enhancement unit (DEU).

assembly should be as small as possible for the radar to be compatible with as many Towers as possible. Considering Control Tower roof dimensions, the horizontal extent of the ASDE-3 antenna/radome is limited to 18 feet.

If because of structural problems or siting considerations the antenna cannot be located on the Control Tower, the ASDE-3 must be able to be configured to allow remoting from a separate ASDE tower to the Control Tower. A review of potential remote tower sites indicates a remoting distance of 8000 feet is needed.

The range-coverage requirements for the ASDE-3 are also dictated by the needs of the candidate airports. Coverage is required from a minimum range of 500 feet to a maximum range of 18,000 feet to satisfy all airports, with the antenna mounted on towers ranging from 40 to 300 feet in height.

Having considered the need for ASDE radars and some of the operational design constraints, let us now consider the parameters of a new radar (ASDE-3) designed to meet these operational requirements.

ASDE-3 DESIGN SUMMARY

In the process of transforming ASTC operational requirements into equipment design requirements, several tradeoff areas were considered. The chosen design approach represents the maximum weather penetration performance possible for a given antenna enclosure size constrained by wind-induced overturning movement considerations. The most interesting features of the resulting design are the integral antenna/rotodome, antenna variable focus, cosecant (CSC) elevation beam-shaping, and pulse-to-pulse frequency agility.

The engineering model ASDE-3 consists of the radar transmitter/receiver and its associated electronics, the antenna/rotodome, the DEU and a test data acquisition system (DAS). The DEU-gated video output interfaces with the NU BRITE video-scan-converted tower cab display (Fig. 4).

The Antenna, Determinant of System Performance

The antenna is the most critical determinant of system performance. It is the predominant factor in the detection of signals in precipitation clutter

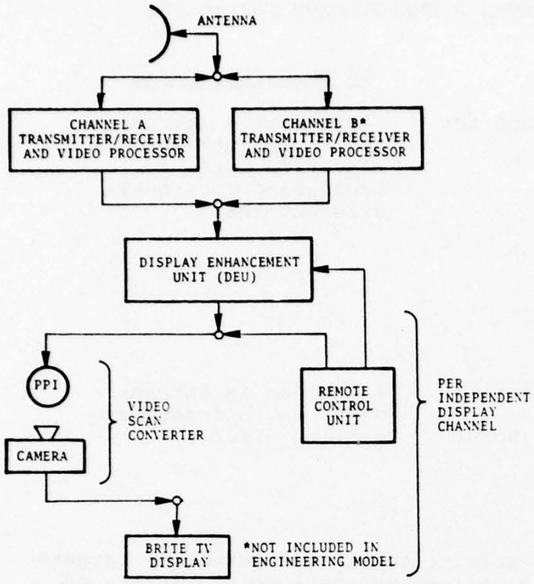

Fig. 4. ASDE-3 block diagram.

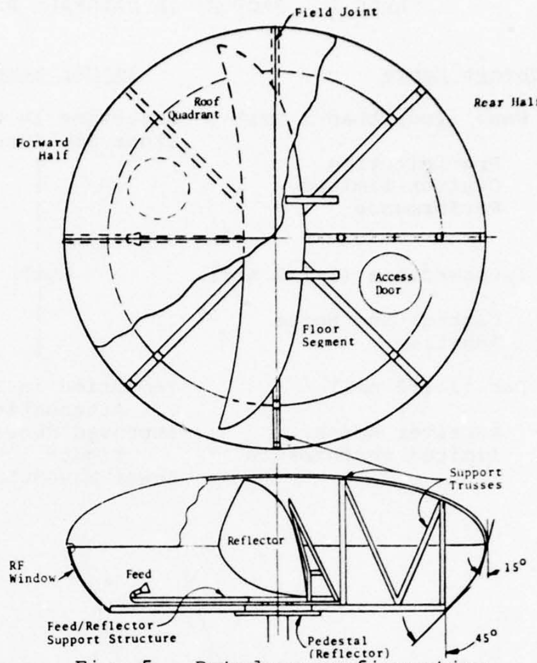

Fig. 5. Rotodome configuration.

and noise and in establishing azimuth resolution. Gain, azimuth beamwidth, and elevation beam-shape optimization are limited by the 18-foot rooftop maximum horizontal dimension. The chosen design takes advantage of the lower rainfall attenuation and backscatter coefficients at 16 GHz (compared with the 24 GHz which was used for ASDE-2), and achieves maximum packaging efficiency by using an integral antenna/radome (or rotodome) shown in Fig. 5.

The choice of the 16-GHz band* was based on a comparison of signal-to-noise-plus-clutter performance in heavy rainfall for 16 and 24 GHz. This comparison showed the lower frequency band clearly superior even for equal physical antenna sizes.

Frequency selection. The radar precipation backscatter coefficient at 24 GHz, the current ASDE-2 assignment, is considerably greater than the value at 16 GHz for heavy rainfall (about 7 dB greater for a 16 mm/hr rainfall rate).[3] Two-way attenuation in heavy rainfall is over 6 dB greater per nautical mile at 24 GHz.[3,4,5] Sixteen GHz also has the benefit of considerably reduced RF attenuation through water film on the radome exterior. The increased antenna performance at 24 GHz, both in gain and in precipitation clutter cell reduction, is more than offset by the reduced *rainfall attenuation* and backscatter cross section at 16 GHz (Table 1). Fig. 6 shows the variation in antenna aperture size as opposed to Signal to Noise Plus Clutter (S/N+C) requirement based on the intermediate-range noise-plus-clutter-limited case. The 24-GHz system requires over 3 times the antenna size to equal the rainfall penetration performance at 16 GHz for the heavy rainfall case at a 2-nautical-mile range. The 16 GHz advantage becomes even more significant if antennas of equal azimuth beamwidth are compared, as indicated on Fig. 6. Although the 1- and 2-foot vertical aperture antennas were included for the analytical comparison, their aspect ratios preclude the use of a simple-point feed-reflector design. As such, they would not be cost-effective antenna candidates for ASDE-3.

The performance differential between 16 and 24 GHz becomes less for the close-range clutter-limited case, but is still 4 to 5 dB in favor of 16 GHz. Because the ASDE range requirement dictates operation in the clutter-plus-noise-limited region, 16 GHz was chosen.

*Actual assignment received for development work is 15.7 to 16.2 GHz.

TABLE 1. FACTORS IN RAINFALL PERFORMANCE IMPROVEMENT FOR 16 GHz

Target Range	16 GHz Benefit	16 GHz Disadvantage
Near (less than 1 nmi) Precipitation Clutter-limited Performance	Reduction in Backscatter Cross Section	Clutter cell increases due to azimuth and elevation beam-broadening for equal-size antenna
Intermediate (1-1/2 nmi) Clutter and Noise Additive	Both	Both
Far (2-1/2 nmi) Receiver Noise-limited Performance	Reduction in Rainfall Attenuation Improved Receiver Noise Figure Lower Waveguide Loss	Reduction in antenna gain due to frequency-scaling effects

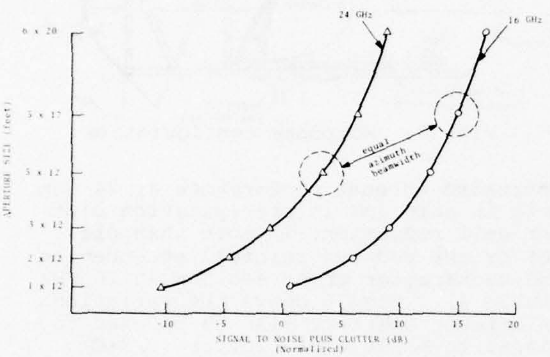

Fig. 6. Aperture size and normalized signal-to-noise-plus-clutter requirement for 16 and 24 GHz at 2 nautical miles in 16 mm/hr rainfall.

Additional factors heavily favoring 16 over 24 GHz are lower waveguide losses and fundamental design considerations allowing much lower noise-figure receivers to be achieved. Lower waveguide loss increases individual site installation flexibility since the transmitter/receiver can be installed farther away from the antenna. The 24-GHz ASDE-2 is limited to less than 30-foot separation between the antenna and the electronics, whereas a 16-GHz ASDE can accommodate up to 100-foot separation.

Integral Rotodome. An overall system azimuth resolution of 40 feet for targets at 6000 feet in range is required to prevent smearing of extended targets and to resolve small point targets on the airport surface. To resolve 40 feet on the NU BRITE display requires an antenna 3-dB azimuth beamwidth of 0.25 degree.* The resulting horizontal aperture giving a 0.25 degree 3-dB beamwidth at 16 GHz is 17 feet, nearly the 18-foot maximum set for the horizontal rooftoop dimension. A 17-foot rotating antenna enclosed in a stationary 18-foot radome would result in (1) excessive shear forces due to the proximity of the antenna tips to the fixed radome, and (2) variations of radome RF transmission characteristics with antenna rotation. The first problem greatly increases drive horsepower and antenna stiffness requirements, and therefore weight and size. The second problem is particularly critical as the angles of incidence through the radome are very non-uniform across the aperture; i.e., considerable radome curvature near the reflector edges. An integral radome (or rotodome) allows more care in the control of an RF window which maintains a constant relationship to the antenna with rotation. Beside making the maximum use of the available enclosure dimensions and optimizing the RF window performance, the rotodome also has a rainshedding

*The convolution of the effective azimuth beamwidth at 6000 feet (26 feet) and the display response (30 feet) gives 40 feet.

advantage. The centrifugal force prevents the formation of a highly attenuating thin film of water over the RF window.

Because of these considerations, the rotodome design was chosen for ASDE-3 (Fig. 5). The shape of the rotodome is a modified ellipsoid, an optimum shape to reduce aerodynamic drag and overturning moment. Comparing the ellipsoid with a spherical radome of the same diameter indicates a 2:1 improvement in overturning moment when measured on a ground plane.

Vertical aperture size and CSC elevation beamshape. Once the horizontal aperture was established at 17 feet, the choice of vertical aperture was dictated by the required peak gain and vertical directivity set by the system rainfall-performance requirements. The approximate 5-foot vertical aperture of the chosen design provides a 1.6 degree elevation beamwidth (at the 3-dB points), maintaining the aspect ratio below 4:1 held critical for a point-source fed reflector.* The resulting peak gain of 45 dBi provides the basis for the 3 mile performance capability of ASDE-3.

The choice of elevation beamshape involves a tradeoff between peak gain on elevation boresight (affecting target returns at maximum range) and gain at high-depression angles (corresponding to targets at close range). In clear weather, receiver noise is the limiting factor in detection. A perfect CSC-squared elevation pattern exactly compensates for the fourth-power range dependence of a surface-target return. Because noise is constant with range, the CSC-squared pattern gives a constant signal-to-noise ratio.

Precipitation clutter returns, however, are range-dependent in the same fashion as the target (Fig. 7a). The use of a cosecant-squared pattern in heavy rainfall results in severely diminishing the signal-to-clutter ratio at close range (Fig. 7b) because the clutter power, contributed largely from the elevation boresight region, is increasing (lower solid line on Fig. 7a) while signal power is constant (upper solid line on Fig. 7a). By comparison, the cosecant pattern maintains a relatively constant signal-to-clutter ratio for the ranges of interest. The elevation beamshape chosen for ASDE-3 is CSC for depression angles from -4 to -31 degrees, achieving the desired S/N+C effect, and is shaped CSC to the 1.5 power from -4 to -1.6 degrees for slightly increased gain. Coverage to a 31 degree depression angle accommodates a minimum range of 500 feet for the tallest ATC tower.

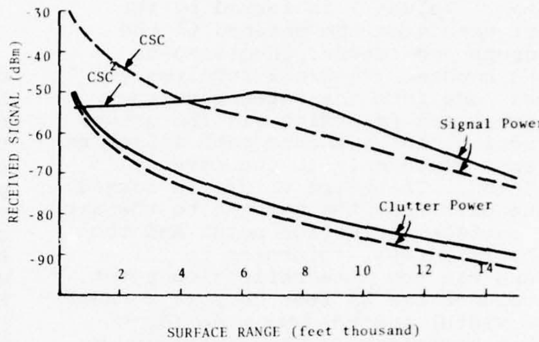

Fig. 7a. Signal, clutter, and range for cosecant and cosecant-squared beamshapes.

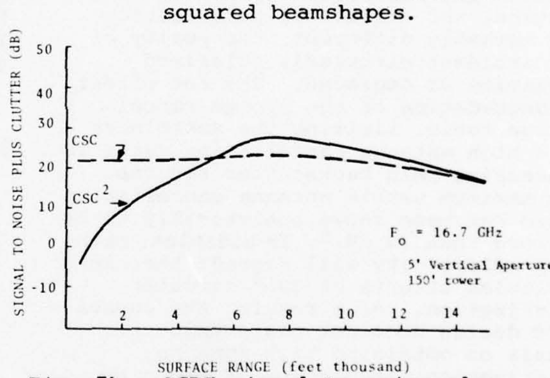

Fig. 7b. ASDE signal-to-noise-plus-clutter performance: cosecant and cosecant-squared elevation beamshapes.

Airport surface effect on cancellation ratio. ASDE-3, as have previous designs, makes use of circular polarization to discriminate between precipitation and target echoes. ASDE differs from surveillance radars in that maximum radar energy is directed toward the ground. Reflection of the ground-directed energy from the smooth airport

*Beyond that aspect ratio, a line-source feed-cylindrical reflector design must be considered, with attendant problems in obtaining adequate dynamic beamshape, weight, and cost.

surface effectively increases the volume of raindrops seen by the antenna, resulting in increased backscatter radiation. Three distinct clutter volumes are formed (Fig. 8), the locations of which are uniquely determined by two constraints:

a. the angles formed by the incident and reflected energy paths with the airport surface are equal (affecting volumes 2 and 3), and

b. the total round-trip path length is identical for all three volumes. Volume 1 is formed by the direct path from the antenna to the raindrops and return, involving no ground bounce. Volume 2 involves two paths: one from the antenna to the raindrops and returning via the ground reflection, and a second path following the same route only in the reverse direction. The third volume is formed by the path from the antenna to the airport surface reflection point and then to the raindrops, returning to the antenna via the same reflection point. The volumes are $\frac{c\tau}{2}$ feet deep (τ = radar pulse width) and $rd\phi$ feet wide ($d\phi$ = azimuth beamwidth). The clutter power from each of the four paths is additive. Because the reflection coefficients for vertical and horizontal polarization are markedly different, the purity of the incident circularly polarized radiation is degraded. The net effect is degradation of the system-cancellation ratio, limiting the usefulness of a high antenna cancellation ratio in supressing rain backscatter returns. The maximum usable antenna cancellation ratio has been shown analytically to be no more than 20 dB.[6] In addition, raindrop ellipticity will degrade the cancellation effects of good circular polarization. As a result, the chosen ASDE design does not place undue emphasis on obtaining high-antenna polarization circularity at the expense of other features.

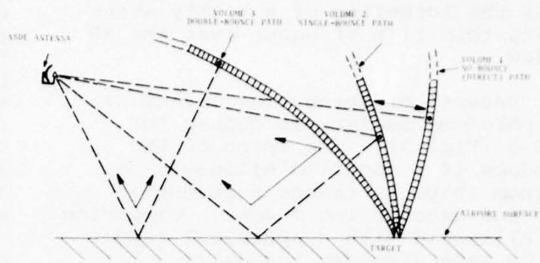

Fig. 8. Clutter volumes causing degradation of cancellation ratio.

<u>Antenna focus as a function of depression angle</u>. The narrow azimuth beamwidth of 0.25 degree necessary to achieve the specified resolution requires an antenna which has a horizontal aperture of about 280λ. At 16 GHz, the near field of this antenna is about 4900 feet. Since the system must operate at surface-target ranges of 500 to 18,000 feet from the radar, some type of focusing is required to accommodate targets at ranges of less than 4900 feet. One approach would be to refocus the antenna for the close ranges and to accept whatever deterioration in gain and beamwidth occurs outside of this focused region. The approach used for the ASDE-3 system is a variable focus antenna whose reflector consists of a series of elliptical horizontal contours whose eccentricity varies with depression angle. (See Fig. 9.) In this technique, the feed horn is located at the primary foci of these ellipses. The major axes are the slant ranges from the tower so that the conjugate foci, as illustrated by F_1, F_2, and F_3, lie on the runway surface. In this manner, the spot size remains essentially constant with surface range.

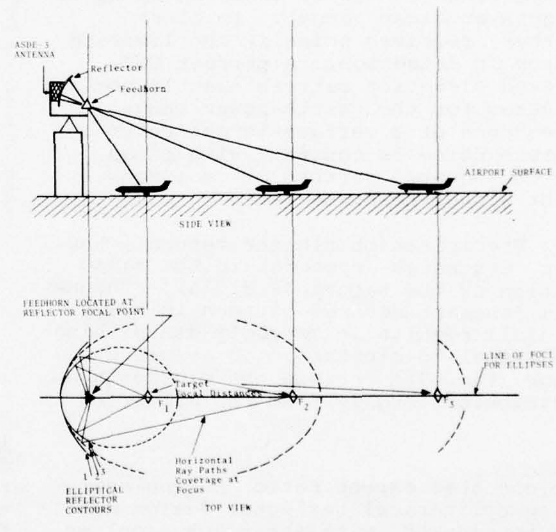

Fig. 9. ASDE-3 antenna focus variation as a function of target range.

Improvement in signal to noise plus clutter is expected from the variable-focus feature since the target on the airport surface will always be in focus while the clutter volume, which extends up from the surface, will be defocused because it is a different elevation angle for that range cell. Defocusing the clutter volume reduces the net backscatter as follows. For ranges within the 4900-foot near-field point, the azimuth clutter cell becomes constant at the horizontal aperture width, having the same effect as increasing the clutter echo power by an inverse-range factor relative to the converging azimuth beam far-field case. The antenna gain in the defocused boresight region decreases commensurate with the azimuth beam-broadening. Because the square of the gain function appears in the radar equation, the net-gain dependence is proportional to the square of range. The combined effect results in an added range dependence in the numerator of the clutter power term, causing the signal-to-clutter ratio to be better by 3 dB per octave for decreasing range than the case where clutter and target are both in the far field.

Frequency Agile Transmitter/Receiver

Another significant departure of the ASDE-3 from its predecessors is the use of a multiple-step frequency-agile traveling wave tube (TWT) transmitter. Benefits from frequency agility are expected in three areas; (a) precipitation-clutter pulse-to-pulse decorrelation, (b) improvement in target-imaging, and (c) elimination of multiple-time-around targets.

Performance benefits of frequency agility. In the contract competition phase of the ASDE-3 program, detection performance was purposely set at a 90 percent P_d and a 10^{-6} P_{fa}*, for a non-fluctuating target specifically to allow ease of performance comparison between radars of widely varying design approaches. Precipitation characteristics similarly were given to prospective builders. Because the actual ASDE environment is not precisely known, characterizing a radar by its single pulse performance for a Swerling case 0 target does not describe performance in imaging real aircraft and vehicles on the airport surface. Rainstorm spatial and temporal characteristics, precipitation backscatter and attenuation values, distributed target models for aircraft, and the extent of cancellation ratio degradation are all areas where experimental data are needed to verify analytical predictions. In particular, if the classical target models described by Marcum and Swerling[7] are considered, the single pulse signal to noise required to provide the specified detection performance for fluctuating targets cannot reasonably be met with a single-frequency radar in the precipitation clutter-limited case. The integration of multiple-target return Pulses cannot be used to reduce input signal-to-noise requirements because rainfall decorrelation time is on the order of milliseconds, much greater than the ASDE interpulse period of 50 to 70 microseconds. It has been experimentally shown[5] that statistically independent samples of precipitation-clutter echoes can be obtained by shifting the carrier frequency on successive pulses. The mechanism by which the decorrelation takes place is analogous to the adding of successive samples of zero-mean gaussian-distributed thermal noise, where the standard deviation of N random noise pulses is on the average 1/N times the single-pulse value. In the case of precipitation clutter, adding successive independent-pulse samples reduces the ratio of the variance to the mean. The normalized frequency correlation coefficient for a rectangular pulse has been derived:[5]

$$\rho(\Delta F) = \left(\frac{\sin \pi\tau\Delta F}{\pi\tau\Delta F}\right)^2 ,$$

where $\rho(\Delta F)$ = Frequency correlation coefficient,
τ = pulse length, and
ΔF = change in transmit frequency.

$\rho(\Delta F)$ goes to zero at $\Delta F = \frac{1}{\tau}$, approximately the bandwidth of the radar matched filter. For non-rectangular pulses, the amount of frequency change required for decorrelation is expected to be less, analogous to the reduced filter bandwidth requirements for a pulse of slower rise time.

*Because ASDE-3 does not incorporate automatic detection, control of false alarm rate is not a priority. The choice of 10^{-6} is based on human-operator tolerance of occurrences per 1-second scan for the total display surface, not taking into account the DEU-mapping function which reduces the active viewing area to less than 10 percent for a typical airport.

The degree of performance improvement is a function of the number of pulses integrated. In the case of the NU BRITE display, at a 20-kHz pulse repetition frequency (PRF), the smallest number of pulses per display resolution cell* is 5 for operationally usable display ranges. Considering the fluctuating target cases for five pulses integrated for the same single pulse signal-to-noise ratio, the frequency-agile system offers far superior detection performance over the non-integrating single-frequency system as shown in Table 2. For the fluctuating target cases, Table 2 shows precipitation clutter-limited detection probabilities of nearly 100 percent for the 5-pulse integrated frequency-agile approach as compared with very poor detection for the single-pulse non-agile approach.

pulse repetition frequency of 20 kHz. Frequency agility is accomplished by radiating at a different carrier frequency on consecutive pulses, up to a maximum of 13 frequencies corresponding to an azimuth beamwidth dwell time. To permit changing the transmit frequency within the 13-microsecond receiver dead time,** a variable-frequency Gunn effect oscillator driving a TWT amplifier was chosen. The receiver and transmitter are maintained at the proper frequency by deriving both frequencies from the Gunn oscillator as a local oscillator (L.O.). An 818-MHz intermediate-frequency oscillator down-converts the L.O. to obtain the transmit frequency (see Fig. 10). For the purposes of evaluating the benefits of frequency agility during field test and evaluation, the agile-step size,

TABLE 2. DETECTION PERFORMANCE FOR FREQUENCY AGILITY COMPARED WITH SINGLE FREQUENCY FOR SIGNAL TO NOISE EQUAL TO 13 dB[8]

Target Case	Frequency Agility 5 Pulses Integrated Percent	Non-Agile Single Pulse Percent
Non-fluctuating (Swerling Case 0)	>99.9	90
Rayleigh pulse-to-pulse fluctuating (Swerling Case 2)	99.4	52*
Chi-squared pulse-to-pulse fluctuating (Swerling Case 4)	99.96	62**

*Single pulse P_d identical for Swerling Case 1 slowly fluctuating target.
**Single pulse P_d identical for Swerling Case 3 slowly fluctuating target.

NOTE: Fehlner's False-Alarm Number = 6×10^5 (see Ref. 8).

Performance margin can also be viewed in terms of a reduction in the single-pulse signal-to-noise ratio requirement for a given detectability. This reduction yields a 12-dB improvement for the 5-pulse frequency-agile approach for a P_d of 0.99 and an 8.5-dB improvement for a P_d of 0.90.

Transmitter/receiver design. The ASDE-3 engineering model transmits a 10-kw peak 36 nanosecond pulse at a

*Given display resolution of 15 feet at the 6000-foot diameter scale.

sequence, and number of steps are controlled by the microprocessor in the DEU in conjunction with an external desk top computer/controller. Step sizes as small as multiples of one-half of the resolution bandwidth (15 MHz) are possible in any sequence within the band of operation. Step sizes as large as 60 MHz (2 times $1/\tau$) are available in a 300-MHz overall bandwidth.

**Fifty-microsecond pulse repetition period minus 3 nautical miles at 12.36 microseconds per mile equal 13 microseconds.

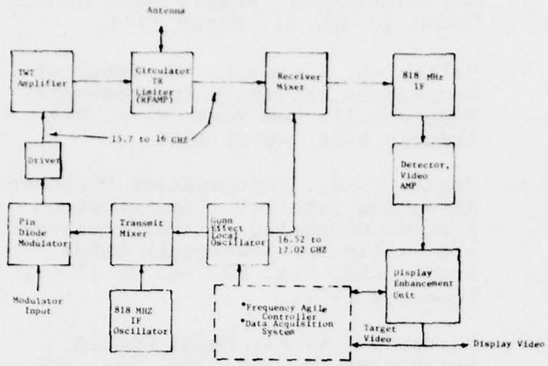

Fig. 10. ASDE-3 transmitter/receiver.

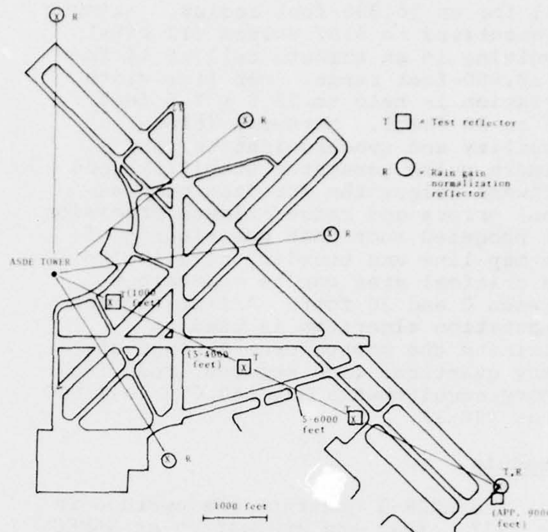

Fig. 11. Location of ÀSDE-3 test and gain normalization reflectors at the National Aviation Facilities Center (NAFEC) Atlantic City NJ.

Thresholding

The ASDE-3 will have a weather adaptive receiver gain control which compensates for changes in precipitation-attenuation path loss. The result is that the return from a given minimum discernible target is maintained constant relative to the display threshold. This feature reduces the receiver dynamic-range requirement and controls the relationship between detected targets and the threshold, such that the tower display will be clear of precipitation clutter even for non-uniform rainstorms over the surveillance area.

Airport surface-mounted reflectors of 10 m^2 radar cross section provide the reference level (Fig. 11). Hardware and software in the DEU in real time examine target levels within a window (range/azimuth-gated area) around each reflector, and compare the value with a clear-weather value stored in the DEU memory. The receiver gain is raised or lowered in accordance with a gain-correction routine that incorporates the range dependence of the attenuation factor and the gain-compensation factors for adjacent reference reflectors. The scheme is particularly useful for a large airport where a total of 12 dB of weather-attenuation gain differential is needed from 0 to a 3 nmi radius coverage in heavy rainfall.

Display Enhancement Unit

An all-digital DEU is part of the ASDE-3 engineering model. In addition to providing the digitally generated map of the airport, and separating areas of interest from suppressed areas (Fig. 3) the DEU provides adaptive receiver-gain control, frequency-agile control, and test-data-collection control functions for the radar system.

The DEU takes rho-theta analog radar video and mixes it with map data in real time, outputting the mixed video to the NU BRITE display system. Map information is stored in and read out of a random access memory (RAM) by radar range and azimuth. Depending upon the setting of an enhance/suppress bit in each accessed memory location, the DEU output is either enabled for critical airport areas or variably suppressed for background areas. The intensity of map lines, background airport-surface feature video, and critical area video are all independently controlled from the tower-cab display-control head.

The creation of the DEU map information is accomplished at the airport site by an interactive process utilizing software residing in the

desk top controller. The map data are stored on magnetic tape, automatically loading into the DEU RAM at power up. Range information is quantized into 2048 cells (11 bits) giving an 8.8-foot range cell for an 18,000-foot radius. Azimuth is quantized to 8192 values (13 bits), resulting in an azimuth cell of 14 feet at 18,000-foot range. Map line-width variation is held to 22.5 $\pm$ 7.5 feet (15 to 30 feet). Hardware (clock stability and synchronization, and azimuth pulse generator stability) and software (algorithm for data compression) errors and range/azimuth precision are budgeted such that positioning of the map line and boundary relative to the critical area can be maintained between 0 and 30 feet. A line-segment computation algorithm is used to eliminate the brute-force storage of every quantized-line segment, reducing memory requirements from 160,000 to 8,000 words (20:1).

Schedule

The ASDE-3 contract was awarded in May 1977. Test and evaluation at NAFEC is scheduled to be completed by the summer of 1979. This schedule supports a FY-80 production procurement.

Conclusion

The ASDE-3 will provide a significant improvement over the ASDE-2. Aside from advances in the state-of-the-art, the improvements are primarily attributable to the use of a lower frequency (16 vs. 24 GHz) and a unique antenna design coupled with the use of frequency agility.

A concern for properly documented user requirements and a top-down systems approach have dominated the selection of ASDE-3 parameters. Parameter optimization against requirements has been central to the design process. The results will be a radar which, while representing a major improvement over the best equipment now available, avoids advanced technologies which were not necessary to meet system needs.

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ACKNOWLEDGMENT

The ASDE-3 radar is being built by Cardion Electronics, a unit of General Signal Corporation, Woodbury NY 11797.

VISUAL CONFIRMATION OF VOICE TAKEOFF CLEARANCE

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BIOGRAPHY

George A. Scott is the Acting Chief of the Training Requirements and Performance Evaluation Section, Air Traffic Control Systems Divison. His career in aviation began back in 1948 with a U.S. Navy air search and rescue group stationed in Honolulu, Hawaii. In 1953, he joined the Civil Aeronautics Administration, Air Traffic Service and served as a communicator in Grand Island, Nebraska and later as an air traffic controller in the Indianapolis Air Route Traffic Control Center. Mr. Scott left the CAA in 1958, to work as Operations Chief at the Wright Air Development Flight Test Center in Dayton, Ohio. He rejoined the FAA in 1959 at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, N.J., where as a project manager, he was involved in such agency programs as: ATC System Concept and Development; Facility Establishment and Environmental Enhancements; Development of Enroute and Terminal Automation; Aviation Weather; Controller Training and productivity.

ABSTRACT

On March 27, 1977, one of the most tragic airport accidents in the history of aviation occurred on Tenerife Island, Spain, snuffing out the lives of 580 people. The probable cause of the accident was a simple verbal misunderstanding of control instructions between the pilot of the departing aircraft and the airport tower controller. This paper addresses a system wherein a stimulus in addition to voice is involved, namely a visual confirmation. Included herein are the basic system requirements, a preliminary system configuration, and a test and evaluation program dedicated to answering the following questions:

1. Does the VICON system improve safety?
2. Is the technique feasible?
3. Can VICON be integrated into the present ATC system?
4. What are the associated costs?

Testing started at NAFEC in April 1978 and it is directed at reducing the system variables to a minimum. Follow-on field testing will be completed at Bradley International Airport, Windsor Locks, Connecticut. The paper closes with a schedule that calls for completing the Bradley tests in March 1980.

BACKGROUND

In just four short years, December 1972 to December 1976, there were seven ground related aircraft collisions in the National Airspace System. Analysis of these accidents has indicated that the probable causes involved controller and pilot judgment of runway usage in takeoff,* landing and runway crossing operations. At present, runway utilization generally involves a single stimulus for receiving air traffic control instructions, that of hearing a voice instruction on the aircraft radio.

In a number of the collisions mentioned above, the probable cause of the accident included a reference to, "the pilot not clarifying ATC instructions." This tends to indicate that present voice (radio) confirmation of runway usage instructions, when not clearly understood by the pilot, can lead to undesirable and unfortunately even unsafe operations. It is questionable whether additional voice confirmation of runway utilization instructions (e.g., repeating the issuance or acknowledgment of a clearance, more detailed instruction such as runway identification, etc.) would be as effective in

* This paper is limited to only the takeoff portion.

gaining the attention (and hopefully eliminating misunderstandings) of controllers and pilot as the use of a second, independent sensory stimulus to positively confirm the voice instruction.

Regardless of the weather, time of day or air traffic situation, the pilot is expected to use sight as a verification of the voice instruction to ascertain if the runway is clear of other traffic before using it. Because of factors such as weather and darkness, positive visual confirmation (Stimulus No. 2) to verify the ATC voice instruction (Stimulus No. 1) prior to proceeding down the runway, is not always possible in todays ATC system.

In order to examine the use of dual sensory stimulus there is a requirement: To determine whether or not visual confirmation of controller voice instructions as they relate to runway operations is feasible, can such confirmation be integrated into the present ATC system and will it provide an added measure of safety? In response to this requirement, the FAA's Systems Research and Development Service initiated, in April 1977, a program to develop, test and evaluate a Visual Confirmation of Voice Takeoff Clearance (VICON) system. In developing the VICON system, the following factors were considered:

1. The confirmation system shall be used as a standard procedure for all takeoffs at airports where there are operational towers, including single and multiple runway airports, and takeoffs at taxiway intersections as well as end of runway takeoffs.

2. The visual reference shall be conspicuous to pilots of all types of aircraft, other then helicopters, prior to takeoff and should have minimal impact on pilots of landing aircraft.

3. The use of the confirmation system should have minimal impact on pilot and controller procedures and on airport capacity.

4. For the controller, a means of activating and verifying the activation of the visual signal shall be collocated and should be readily accessible to the controller and separate from other lighting controls.

5. The visual signal shall be distinguishable by the pilot from other visual aids in takeoff areas including displaced threshold areas and shall meet current airport siting criteria for runway lighting systems.

6. If the takeoff visual confirmation concept proves to be operationally feasible and beneficial, it may be used as a basis for a similar visual confirmation system for runway crossings .

SYSTEM DEVELOPMENT AND TEST

As presently defined, the VICON system is basically a set of signal lights located adjacent to the runways at takeoff locations and a system control panel located in the tower cab. These two components are connected by either hardwire or radio control links. Various techniques for automatically controlling the intensity of the lights and for turning the lights "off" after manual activation by the tower controller are being tested.

To determine if a visual signal confirming a takeoff clearance is operationally acceptable and technically reliable, a two-phase evaluation was selected. Phase I, which is being conducted at the National Aviation Facilities Experimental Center (NAFEC) Atlantic City, New Jersey, is designed to provide prototype system development and initial operational testing; Phase II involves the procurement, installation, testing, and evaluation of a total VICON system at the Bradley International Airport, Windsor Locks, Connecticut.

a. Phase I Test Environment

To carry out the initial technical and operational tests of the VICON system, runway 13. 31 and taxiway India (Figure 1) at NAFEC

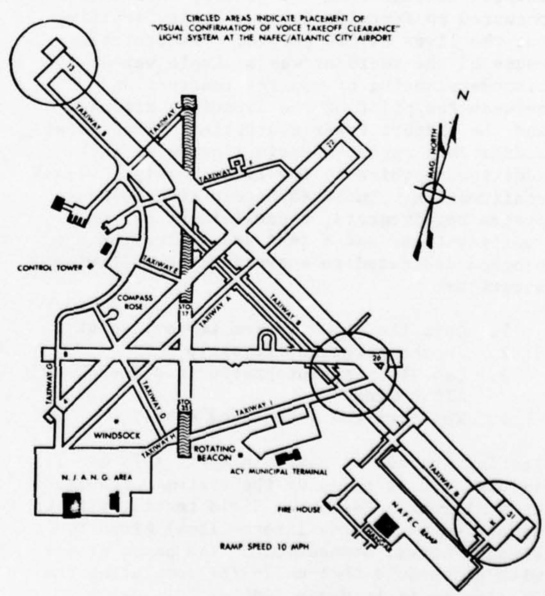

FIGURE 1. ATLANTIC CITY/NAFEC AIRPORT, ATLANTIC CITY, NEW JERSEY

was selected to serve as the test location. Also shown in Figure 1 are the initial locations of the light fixtures, which are standard highway traffic signal lights (Figure 2) complete with green lens and

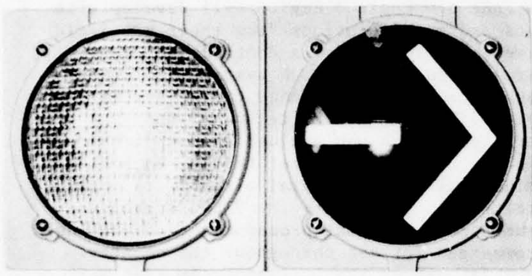

FIGURE 2. STANDARD HIGHWAY TRAFFIC LIGHT

a 100 watt bulb. Variations of this initial test arrangement will include:

Lens color - red, green/red, green arrow, white strobe/green
Bulb Wattage - 200, > 200 watts
Fixture Posture - Horizontal
Unit Arrangement - Triangular (3 lights)
Light Configuration - 5 @ 200', 4 @ 300' and 600'
Viewing Angles - 5°, 10°, 15°
Lamps - PAR 56 in green and red (6 @ Runway 13 only)
Louvers and Blinders - Single and multiple axis, eyebrow

The VICON lights are controlled from a control panel located in the Atlantic City (ACY) tower cab. As shown in Figure 3, the panel layout is a representation of the ACY runway and taxiway layout and contains several controls for activating the various operational functions. In addition to the console mounted VICON control panel, a remote control switch will be tested. This switch, allows the controller to move freely about the tower cab and not have to return to the console mounted panel each time an aircraft is cleared for takeoff. This remote control, which may be attached to the controller's belt, is capable of controlling the VICON signals from any two departure points.

An integral part of the Phase I development and test activity is to determine the best technique for deactivating the VICON runway lights once they have been activated by the controller. Following the ATC clearance, "Cleared for takeoff," the controller selects the button on the tower control panel that will illuminate the VICON runway light that is located in the area of the departure aircraft. Once the pilot has aurally acknowledged the voice instruction and visually observed the light, there is no longer a need to display the VICON signal light. In fact, it needs to be extinguished so that a following aircraft does not interpret the light to mean that he is cleared for takeoff. Previous programs involving runway signal lights have shown that in order to eliminate the possibility of leaving the "cleared to go" lights in the "on" position, automatic deactivation of the signal lights, not requiring controller intervention, is a mandatory operational requirement. Hence, three techniques for automatically extinguishing the VICON lights are being evaluated.

1. Automatic Timer - Countdown deactivation device that is preadjusted to turn "off" (in seconds) each VICON runway or intersection takeoff position light. (Not a feature provided on the tower control panel).

2. Microwave Intrusion Device - Detects passage of an aircraft as it passes between the microwave sensors, deactivating previously illuminated VICON lights.

3. Induction Loops - Buried in ends of runways 13/31, senses aircraft passing over the loops extinguishing the visual clearance lights.

A major concern in airport lighting is that of lamp intensity under varying degrees of meterological conditions and day/night operations. The VICON lights, available 24 hours a day, must be bright enough to be seen during sunny days (with the sun shining directly into the lens) and controllable (to a lower intensity) at night so as not to cause glare in the pilot's eyes. Two schemes for providing control of the VICON signal light intensity are being evaluated: automatic intensity control using photoelectric cell; manual control provided on the tower cab control panel. Selectivity of the automatic feature or the manual five step intensity level control are provided on the mimic panel as shown in Figure 3.

The VICON control panel located in tower cab and the clearance lights located on the runway 13/31 and taxiway I are interfaced through a hardware control line link. Also, two commercial radio control links, to runways 13 and 31 will be evaluated during this Phase I effort.

b. Test Methods

Conclusions from tests conducted on the variables of the Phase I VICON system will be based solely upon the response from the users. The response from the pilots and controllers will be obtained from comments received via prepared questionnaires or

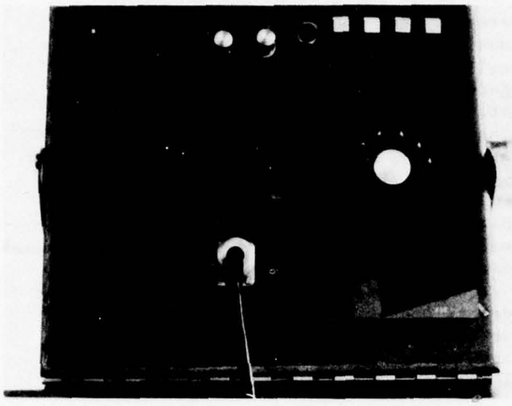

FIGURE 3. PHASE I VICON TOWER CONTROL (MIMIC) PANEL

received verbally via radio or telephone.

Prior to changing the VICON system configurations, the NAFEC user or pilot organizations will be notified as to the change being made, and date and time that the new configuration will be operational. To obtain an early response to each change, NAFEC pilots will be introduced to the new system variation by: (a) NAFEC aircraft conducting simulated takeoffs; (b) radio-equipped vehicles - pilots taken to departure points; (c) regular project flight schedules - use of questionnaires and telephone debriefing.

c. Data Collection

Due to the operational nature of this particular program practically all of the data, except for equipment reliability data, will be of a subjective nature and will be collected by means of:

1. Voice or tone actuated tapes of the tower cab controller (local) position.

2. Controller responses to prepared questionnaires.

3. Pilot responses to prepared questionnaires.

d. Phase II - Test Environment

Based on a technical description developed from the Phase I NAFEC efforts, a VICON system will be installed on all runways and tested at the Bradley International Airport (BDL), Windsor Locks, Connecticut. BDL was selected for the following reasons:

1. Traffic load and distribution representative of moderate size commercial operation, including international, national, shuttle, general aviation and some military flights.

2. Sufficiently complex runway configuration to provide meaningful demonstration of VICON system effectiveness in maintaining traffic flow.

3. User personnel (pilots and controllers) with favorable, neutral pretesting attitudes.

4. An airport administration that supports the objective of the evaluation program.

The FAAs New England Region will develop site plans and specifications from their BDL field survey, and then award a contract for the installation of the VICON system. Following installation and acceptance of the system, NAFEC will commence the technical and operational test and evaluation exercises. This operational/technical testing at BDL, a medium density, commercial airport, is most vital for it represents the VICON system and associated conceptual procedures that will be recommended for use throughout the country. For this part of the overall VICON test and evaluation, all of the runways ends and the intersections with taxiways (Figure 4) at BDL

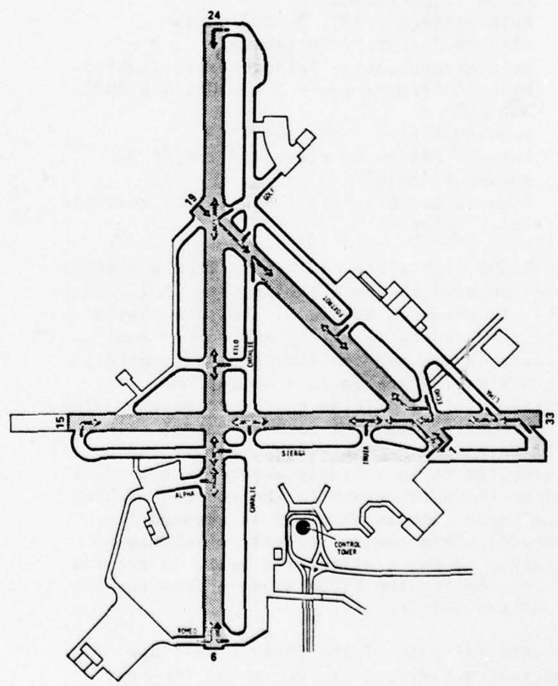

FIGURE 4. BRADLEY INTERNATIONAL AIRPORT, WINDSOR LOCKS, CONNECTICUT

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will be equipped with the VICON light configuration as developed in Phase I. Proper location and aiming of the 55-60 lights: in 24 locations at BDL will be a real test of the technical portion of the program. The need to provide noninterfering lights at the intersection of runways 33 and 1 and taxiways S and E may dictate the requirement to use other types of visual signals, e.g., taxiway identification lights, signs, etc.

Previous tests of airport traffic signal lights (Reference 1) have provided several very important conclusions: (1) Any device placed in the tower cab that diverts the controller's attention away from his primary job of visually controlling traffic could lead to an unsafe situation; (2) A complicated, complex control panel located in a less than optimum location is not acceptable (most tower cabs have very little space, especially at the local control position, for installing additional control panels); (3) At the larger busy airports, the addition of control personnel may be necessary.

Two types of control panels will be tested at BDL. A mimic panel, representing the layout of the BDL runways and taxiways, shown in Figure 5, and a matrix panel as shown in Figure 6 are being considered for evaluation.

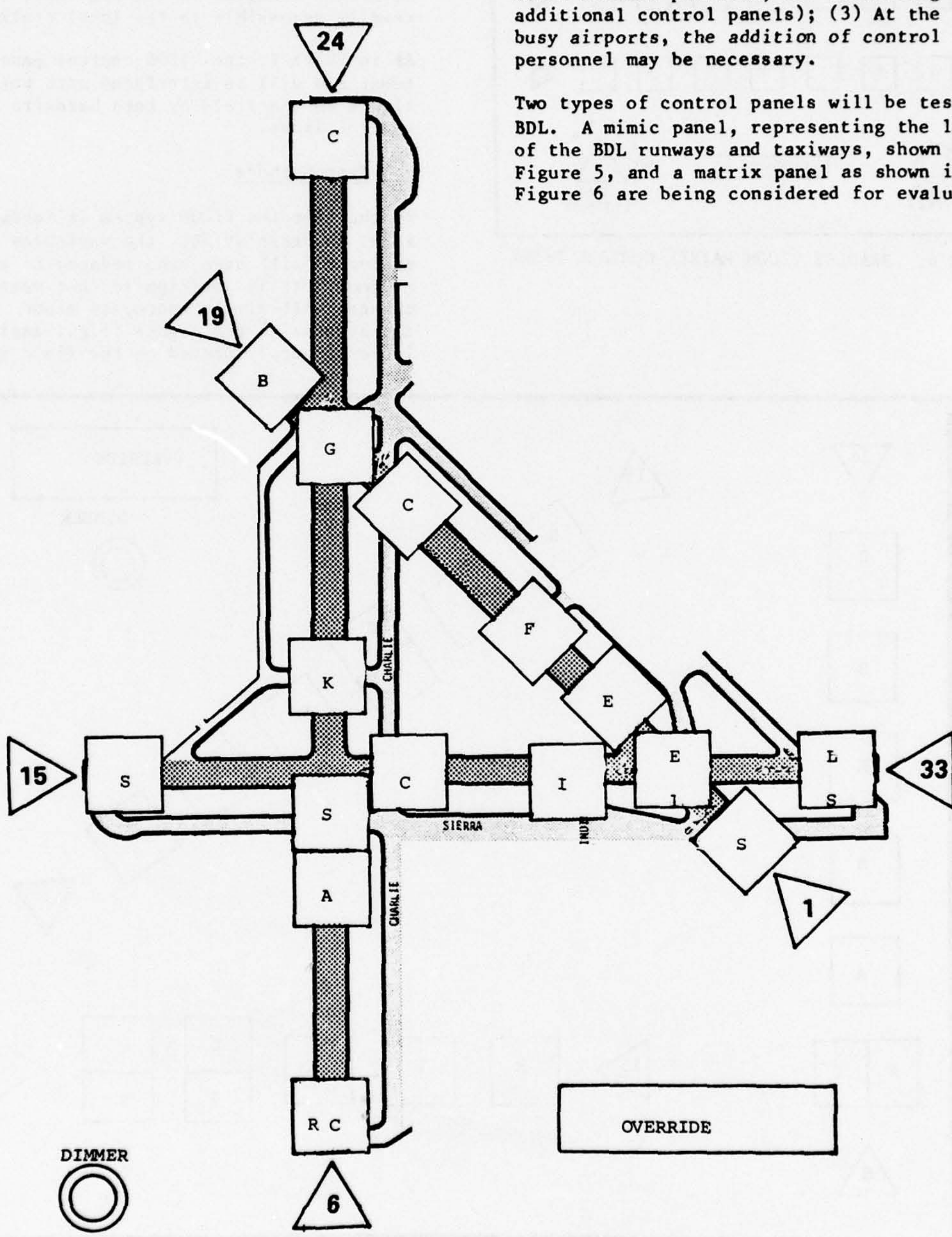

FIGURE 5. BRADLEY VICON MIMIC CONTROL PANEL

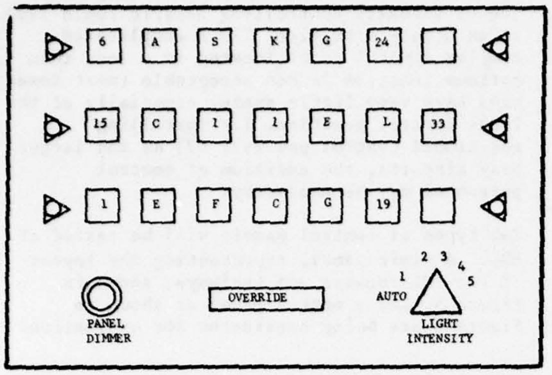

FIGURE 6. BRADLEY VICON MATRIX CONTROL PANEL

The remote control panel, a part of the main control panel, will be evaluated in conjunction with each console mounted main panel. A combination of the two panels, as shown in Figure 7, is another possibility. Human factors application exercises and laboratory test and evaluation efforts are planned to provide a simple, effective and efficient control panel. Fortunately the panel will be mounted in an exceptionally desirable location in the BDL tower that is readily accessible to the local controller.

As in Phase I, the VICON control panel in the tower cab will be interfaced with the VICON lights on the field by both hardwire and radio control links.

e. Test Methods

By the time the VICON system is installed and ready for test at BDL, the variables to be evaluated will have been reduced to a very mimimum. It is anticipated that most of the changes will simply encompass minor adjustments to the lights (e.g., angles, louvers, etc.) located on the field and

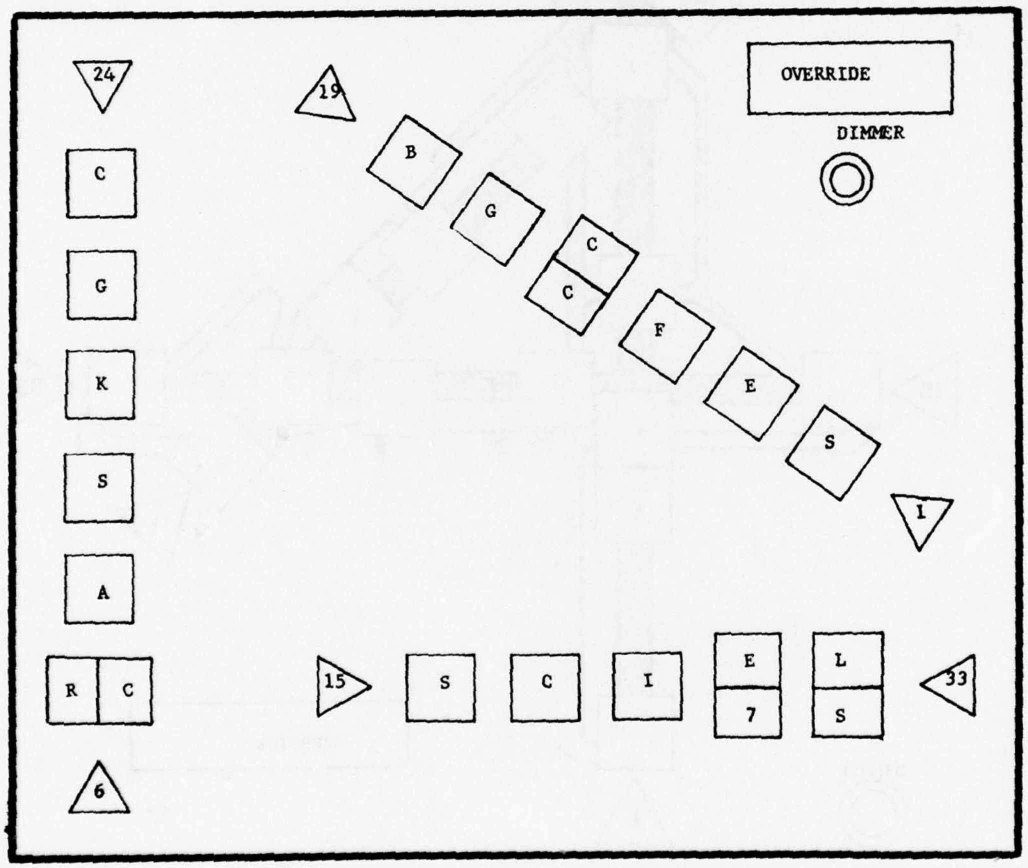

FIGURE 7. BRADLEY VICON MIMIC/MATRIX CONTROL PANEL

possibly minor modifications to the tower cab control panel. During the Phase II test period a technical log will be maintained of the performance of each VICON subsystem so that at the end of the test period, the suitability of each component can be determined. The BDL technical evaluation data will be used to determine: (1) system reliability; (2) cost effectiveness (3) installation criteria and maintenance details.

The operational evaluation at BDL encompasses the basic technique used during the Phase I effort; i.e., pilot and controller reactions to the system. Questionnaires for these user groups will be prepared and administered only after extensive efforts to familiarize the controllers and pilots with the VICON system has been accomplished. Efforts are underway to develop means of obtaining more objective data for this phase of the program, such as air traffic delays, aborts, communication repeats, workload, etc. Depending on the controller workload under heavy traffic conditions, it may become necessary to add a VICON controller to the tower team.

f. Data Collection

Information about the controller's attitude toward system effectiveness will encompass four areas of concern:

1. The capability of a properly designed and operating VICON system to provide the pilot with confirmation information comparable to currently used radio only techniques.

2. The degree of confidence in the accuracy and reliability of VICON performance to the extent that the safety of surface traffic is maintained.

3. Reactions to the installation and suggestions for modifications and improvements. This includes technical items such as panel location and size, switch sizes, etc., and such operational items as the requirement for and procedures pertaining to an additional VICON controller.

4. Subjective reaction on affect to controller workload listed above can be summarized to obtain the general consensus of controllers concerning the VICON. Where questions dealing with specific items of interest; e.g., safety, visibility limitations or conflicting message resolution, differ significantly in the number of favorable and/or unfavorable responses, these differences can be used as diagnostic tools for system improvement, or as trade-offs in the overall assessment of VICON versus other methods of confirming takeoff clearance.

Analysis of these results should pay particular attention to the experience of the controller responding and any change in attitude or response which occur many times (repeated submission) during the test schedule.

Since the pilot will be the ultimate beneficiary of the system to be used for takeoff clearance confirmation, his responses are critical to acceptance of the VICON concept. Information concerning four areas of pilot attitude will be obtained through use of the questionnaire:

1. Does the takeoff clearance confirmation signal reduce or increase pilot workload during normal operating conditions?

2. Is sufficient information provided by the visual signals to maintain traffic flow efficiency and safety without excess radio contact?

3. Does the use of the signal permit safe takeoff clearance confirmation under severely limited visibility conditions?

4. Is there a positive overall reaction to the VICON signal concept and are there suggestions for modification and improvements?

The data obtained from pilot questionnaires will be treated in essentially the same manner as that derived from the controller. In analyzing these data, particular attention must be paid to any differences in response associated with aircraft type, familiarity with airport, and nationality (language facility) of pilots.

SCHEDULE

Installation of the NAFEC VICON prototype system was completed in April 1978 and testing commenced the following month. The NAFEC test and evaluation exercises will be completed during 1978. If everything goes according to schedule, the BDL VICON system should be completely installed and ready for field in-serice test and evaluation in August 1979. The BDL tests will run until March of 1980 and the technical data package should be completed the following month - April 1980.

SUMMARY

To avoid the tragedy of another Tenerife, a technique for confirming the controller's voice takeoff instructions is being developed, tested and implemented. The mission of the VICON system, which is the manual forerunner of more sophisticated automated systems yet to be developed, is to improve safety; its role is to provide a second sensory stimulus to confirm voice takeoff clearance. Four major questions that must be answered during the NAFEC and BDL tests are:

1. Does the VICON system improve safety?
2. Is the technique feasible?
3. Can VICON be integrated into the present ATC system?
4. What are the associated costs?

The technical engineering data and the operational data gathered during the planning, installation, test and evaluation of the VICON system at NAFEC and BDL will be used to develop a Technical Data Package (TDP). If the answer to the first three questions stated above is "yes," then the TDP can be used for providing an engineering standard for operational implementation of VICON at other airports in the National Airspace System if the cost results (question 4) are favorable.

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CENTRAL FLOW CONTROL AUTOMATION - AN EVOLUTIONARY APPROACH

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Biography

Dr. Carlo J. Broglio is a member of the Program Manager Staff, ATC Systems Division where he serves as the Program Manager for the Federal Aviation Administration's Central Flow Control Automation Program. He received the Ph.D. and M.S. degrees from the University of Maryland and a BEE degree from the University of Detroit, graduating cum laude. Prior to joining the FAA in 1973, he spent 10 years with NASA as a program manager and research consultant in the data processing field. Dr. Broglio's primary interests are software engineering and the management of large complex system development programs. He is a member of the IEEE, the AMA, the AIAA, Eta Kappa Nu, and Tau Beta Pi.

Thomas L. Hannan is a member of the Program Manager Staff, ATC Systems Division. He received the B.S. degree in Information Systems Management from the University of Maryland in 1970, and has done graduate work in Management Science at the University of Maryland and the George Washington University. Prior to joining the FAA in 1976, he spent 2 years with the Social Security Administration as a project manager and 3 years with Computer Sciences Corporation in line, staff, and project management. Mr. Hannan's primary interests are software engineering and quantitative methods; he is a member of the IEEE, the AMA, the Society for Management Information Systems, and Beta Gamma Sigma.

ABSTRACT

This paper presents an overview of the Central Flow Control Automation development program. It begins by presenting the historical development of the central flow control functions. The basic requirements of a flow control system are then developed. These requirements are then expanded into a set of functions which the operational system must satisfy. The products, expected results, and status of the current development program are then presented. The benefits expected to be derived from this system are listed and where possible quantified. An overview of the technical approach relating to the functional approach is then presented. The paper ends by presenting several areas in need of improvement and identifying areas where more basic research is needed.

In summary, this program is establishing an operational Central Flow Control Facility in Jacksonville, Florida, complete with a 9020A computer, nationwide communication, intelligent terminal data entry devices and selfcontained software support. This is being done to give the nation the opportunity to reduce aviation fuel consumption by one million gallons per month. The basic system has operational shortfalls in the areas of information dissemination and detection of demand termination. Further, more basic research is required to understand the concept of system capacity.

BACKGROUND

a. Historical Perspective

The Air Traffic Control System Command Center (ATCSCC) was established in

1970 to oversee the flow of aircraft among the Air Route Traffic Control Centers. Its primary objective is to coordinate the flow of air traffic among the nations ATC facilities to balance traffic loadings and to minimize delays.

Prior to the establishment of the ATCSCC, flow control concepts were primarily reactive and defensive. In general, individual facilities tended to adjust the flow of traffic in response to problem situations without giving adequate regard to their effect on the rest of the ATC system.

In an attempt to reduce the proliferation of flow restrictions, the Air Traffic Service established an experimental centralized flow control facility in December 1968. Limited automation support for the facility was provided in January 1970 by using a MITRE programmed IBM-9020A simplex system located in the Kansas City ARTCC. (Reference 1) The automation support was primarily in the area of predicting demand at large terminals to support Advanced Flow Control Procedures (AFCP) (Reference 2) developed by the Air Traffic Service. Due to the success of the experimental facility, in mid-1970 it was made a permanent part of Air Traffic System.

In 1971, the FAA projected an ever increasing workload requirement for the ATCSCC and a decision was made to begin an evolutionary development of more advanced Flow Control Procedures. Since the demands for computer resources at the Kansas City ARTCC would exceed the available capacity if the flow control automation program remained there, and since further refinement and experimentation was required to develop the procedures required by Central Flow Control, the Transportation Systems Center was tasked with developing an experimental prototype flow control system. In January 1972, a program named the "Airport Information Retrieval System" (AIRS) was placed in operation by the Transportation Systems Center using a commercial time-shared computing system. (Reference 3) This prototype system has been used by the Air Traffic Service to support Central Flow Control operations from 1972 to the present time. Refinements and modifications to the original AIRS have been tested in an attempt to define the basic functional capabilities required of a fully operationally automated Central Flow Control Facility to be incorporated into the National Airspace System.

In December 1975, the Air Traffic Service documented the basic requirements of an automated flow control system based upon almost 4 years of experience with AIRS. (Reference 4) These basic requirements underwent detailed analysis by an interservice task force comprised of Air Traffic Service, Airway Facility Service, Systems Research and Development Service, Transportation System Center, and contractor personnel; and a detailed specification for an Advanced Central Flow Control Facility acceptable to all participating Services was produced. (Reference 5).

b. <u>Current Program</u>

The requirements documented by the Air Traffic Service formed the basis for a development program which will result in a commissioned flow control facility.

The general objective of this program is to define and develop the automation support required to improve the efficiency of National Airspace System (NAS) management operations in the ATC System Command Center. The specific objectives of the program are:

1. Develop a computer-based system for the central flow control function of the ATC System Command Center to process data pertaining to status and loading of the high density terminals, and to provide the associated systemwide forecasts of traffic overloads and alternative flow control measures.

2. Develop the communications and software capabilities for interfacing the System Command Center Automation System with NAS En Route Computer System.

3. Develop a system support facility that is capable of sustaining the ongoing operation and maintenance functions required by the Air Traffic Service.

4. Establish and train a Data Systems Specialist staff capable of performing the necessary maintenance and development activities required for the orderly evolution of the Central Flow Control Function.

The fulfillment of these objectives will be examined by tracing the development process from the requirements definition phase through the functional specification phase.

REQUIREMENTS DEFINITION

Flow control in the broad sense exists for the purpose of balancing the air traffic demands for service with the air traffic control system capacity to handle those demands. As demand approaches capacity, the requests for service become delayed at an exponential rate. This causes an increase in the number of aircraft under control of a single controller and represents a significant increase in workload. Care must be taken in approaching the solution to this problem because certain solutions would require the system to operate below its capacity even though a heavy demand existed. (Reference 6).

The flow control process can be thought of as a set of discrete flights operating over a time period in which this set will occupy runway positions. Flow control problems arise whenever the sum of the scheduled flights for a given time period exceed capacity of the the runway for that time period. The desired objective of the discrete flow control process is to shift the excess flights to time periods which can accommodate them.

Regardless of the objective function defined, its variables, or their coefficients, any attempt to optimize will consist of the management of aircraft and facilities in a prescribed manner. (Reference 7)

a. System Scheduling. This is the planning requirement. There is a need to establish a first feasible solution to the basic demand/capacity problem that exists in any system having scarce resources. The flow control system must provide the mechanism whereby the baseline facility capacity schedules may be known and manipulated. There must also be provision for dynamic schedule updating.

b. Problem Investigation. Once the planned demand and planned capacity schedules are known, and a mechanism for maintaining the currency of these schedules is provided, the flow control system must supply a means for recognizing an imbalance and determining its severity. The system must allow assessment of the impact of adverse weather on major facilities; it must also allow adjustment of aircraft schedule changes made in response to the adverse weather. This capability forecasts the state of the system if no intervention occurs.

c. System Evaluation. Upon determining that the forecasted state of the system is such that the objective function is not being optimized, a decision to intervene will be made based on the magnitude of the problem. The flow control system must be able to forecast the effect of proposed control strategies in order to determine their applicability. Furthermore, the system must contain the mechanisms required to enable an after-the-fact evaluation of the actual effects of the strategy that was implemented. This is the feedback loop that will be used to refine system strategies and procedures.

d. Coordination. The scheduling, investigation, and evaluation requirements addressed above additionally require the synchronization of all involved parties' perception of a situation. The organization responsible for flow control must be knowledgeable of both aircraft and facility operations if there is to be acceptance of the selected solution strategy. In addition to this synchronization aspect of coordination, the flow control system must provide the mechanisms for implementating an optimization strategy. The accuracy, completeness, and timeliness with which the flow control system addresses this requirement is critical.

FUNCTIONAL SPECIFICATION

In order to meet the requirements identified above, it becomes clear that a minimum set of functions which must be performed by an automated system can be specified. These functions can be grouped into five major areas: data collection, data analysis, alternative selection, information dissemination, and performance evaluation.

a. Data Collection. The system must be able to access, in machine-readable form, the planned demand schedules and the planned capacity schedules. It must further be able to modify these schedules to reflect any changes in demand and/or capacity. The ideal goal would be to know in complete detail the status and composition of both the entire demand and capacity components of the system. At a lower level of detail, all of the classic communications and information-storage functions must be provided.

b. Data Analysis. For the investigatory aspect of flow

management it is necessary to be able to analyze the stored information regarding demand and capacity. The flow control system must provide a set of statistical functions or models depicting the demand/capacity relationships in a manner that enables recognition of an imbalance or suboptimization that exceeds some threshold value. Implicit in the provision of this functional capability is the ability to access the information stored and maintained as a result of the data collection function, and the further capability to display analytical results in a meaningful fashion.

c. Alternative Selection. Functionally, this is related to data analysis in that it requires the forecasting capabilities of a statistical or simulation model, as well as the implicit support functions noted above. The major distinction to be made is that the data analysis function is performed on the normal data base which contains the "best-estimate" of the real situation, while the alternative selection function must deal with one or more sets of hypothetical data. This function has as a mandatory specification a feasible solution, and as a desirable specification an optimal solution. Initially, due to general lack of historical data and inability to agree on an objective function, implementation will necessarily be limited to selection of the "most optimal" (with respect to some simple objective) of several alternative strategies.

d. Information Dissemination. The system must be able to distribute flow control information and advisories to concerned parties, both demand and capacity organizations. The timeliness and accuracy of the distribution are limiting factors on the "controllability" of the flow situations, and lend themselves to stringent performance as well as functional specification. As in the data collection function, implicit subfunctions exist. These must include communications and device-dependent formatting considerations. The functional capability to route classes of message to predefined distribution lists should be available.

e. Performance Evaluation. Two related functions are included here; evaluation of the effectiveness of the flow control strategy employed in a given situation, and the overall effectiveness of the flow control system in the management objectives established. The first requires a feed-back function operating in a near-real-time environment, the second requires on-line recording functions and off-line analysis functions which will operate on those recordings. Precise definition or functional specification of these functions is extremely difficult until some experience with the system has been obtained under real operating conditions.

PRODUCTS AND EXPECTED RESULTS

This program is to be accomplished over a 3-year performance period and will produce the several major products described below. The program has been ongoing for 2 1/2 years to date and has many of its major accomplishments already in place with several significant projects still to be done. There are areas of benefit to both the FAA and the user community that this program will have to achieve.

a. Major Program Products

These are items that represent either an increase in the FAA's resource inventory or a mechanism to better utilize the existing resources. The products fall into three broad categories; facilities, software, and staffing.

1. Facilities. A building to house the operational facility was constructed on the grounds of the Jacksonville ARTCC. An FAA owned 9020A computer system was established as the central flow control computer. New data terminal and entry devices were procured for the Systems Command Center. A nationwide communication link to the 20 ARTCCs was established.

2. Software. Computer software that runs on the 9020A computer was developed to support all aspects of the program. Routines were designed to implement the operational capabilities defined by the Air Traffic Service in their requirements statement. A software support system was installed to allow the Data Systems Specialist (DSS) staff to maintain and enhance the basic operational software system. Hardware diagnostic aids were developed to assist the Airway Facility technicians in maintaining and certifying the total system.

3. Staffing. A DSS staff dedicated to the flow control activity was hired

and trained to perform the necessary maintenance and development activities. The flow control specialists will be provided with a revised operational procedures manual which will allow them to effectively use the new system. A data base administrator is to be trained in the modern techniques required to keep the system accurate and responsive.

b. Accomplishments To Date

The development program began in January 1976. A request for proposals was released in May 1976. Concurrently, an in-house technical team was busy producing a functional specification which was approved in August 1976. The competitive procurement process ended in April 1977, with the award of a software development contract to Computer Sciences Corporation (CSC). The Airway Facilities Service hired a construction contractor who completed the building in Jacksonville in August 1977. CSC completed their high level program design specification in August 1977 (Reference 8) and moved to the Florida site in September. The FAA completed a critical design review of the software system in November 1977 and coding began. The first major program capability was delivered by CSC in February 1978. In April, the data storage and retrieval software became functional and the Air Traffic Service released to the ARTCCs the communications software. In May, the full multiprocessing capability of the flow control system became functional.

c. Future Events

In July 1978, the Airway Facilities Service will install the new data terminal and entry devices on the computer thereby completing the hardware additions. Also, in July, the real-time interface with the ARTCCs will become functional. The total software system will be completed in September. The training of the DSS staff will be completed in October. The documentation will be finalized and the system will become operational in December 1978.

d. Benefits

The benefits of this development program fall into two broad categories; FAA benefits and user benefits.

1. FAA Benefits. The accuracy of the data base will be enhanced in the new system by the addition of real time flight static data to the static OAG flight files. The new system will be maintainable and modifiable since it will be fully documented according to FAA standards. The reports to the flow control specialist will be expanded to obtain demand routes or selected fixes as well as airports. The system availability to the command center will be governed by a fail safe/fail soft design. In the operational area, the aircraft holding stack size at all airports will be reduced to a 30 minute level and the flow control fuel advisory departure range of effectiveness will be extended to nation-wide coverage.

2. User Benefits. The present ATCSCC system was reviewed and the following types of benefits were identified due to Central Flow Control Automation: (Reference 9)

(a). Greater ATC system operating efficiency

(b). Increased safety

(c). Reduced aircraft operations costs, including fuel consumption, due to the transfer of delays from the airborne holds to ground holds by usage of Fuel Advisory Departure (FAD) procedures

(d). Increased accuracy in advisories to aircraft operators of anticipated arrival delays and their forecasted length, thereby giving the user the option to reschedule flights and reduce diversions and cancellations

(e). Improved reaction to a major unscheduled outage such as the loss of communications at a center

In performing a detailed analysis of the available data, significant quantifiable benefits were found only in area (c). above. The primary quantifiable benefit in this area was in the reduction in fuel consumption attributable to the transfer of airborne delay to ground delay through the implementation of FAD procedures. This reduction will be on the order of 1 million gallons of aviation fuel saved each month the system is operational.

TECHNICAL APPROACH

The definition of the flow control problem at an overall requirement and at a general functional level appears to have industry agreement. The subsections that follow describe the current problem solution being

implemented and address those areas in which enhancement would be of most value. The description is presented in two steps; the system components description, and the system activity description.

a. System Components

The system is comprised of, and limited by, its basic components; data and software. In each of these areas an attempt has been made to obtain a basic but extensible capability, so that the system will lead to the knowledge necessary for gradual evolutionary development.

1. Data Description. The data is the substance of the system; the timeliness, accuracy, and completeness of the data describe boundaries of effectiveness which the system cannot surpass. Two types of data need to be collected and maintained; capacity data and demand data.

(a). Capacity Data. Departure from remote points cannot be precisely controlled to match the receiving capacity of an airport or sector because the system capacity is a variable. Historical data and other factors are used to make the best estimate possible for the system capacity over an operational day, but many unpredictable factors will change the acceptance rate in varying degrees. Several examples of such factors are a windshift or a lower ceiling forcing the use of a less desirable set of runways, a thunderstorm or low visibility which closes the airport for an unexpected period, runway closure due to snow removal, or disabled aircraft.

(b). Demand Data. Demand is also a variable. The number of aircraft desiring to use an airport cannot be precisely predicted in advance. Extra sections, air taxi and random itinerant requests are received with little advance notice. Furthermore, weather can create major changes in demand. An airport closure can place a large burden on nearby airports. For example, when Kennedy airport is closed, the traffic demand on La Guardia and Newark is increased. Furthermore, when Kennedy is reopened, a surge in demand may be expected from Philadelphia, Boston, Baltimore, and Montreal. This is a large, short-term demand that could not be scheduled in advance, and this demand must be merged into the scheduled traffic that was unaffected by the closure.

2. Software Configuration. The computer programs being developed are organized in such a way as to allow the most evolutionary flexibility. The analytic portions of the programs are buffered from the hardware dependencies of their environment wherever possible. Device-dependent aspects are handled by special communications software, physical data storage dependencies are handled by special data management software. Finally, invocation and processing control is retained in supervisory programs whose execution is transparent to the analytical programs.

(a). Communications. Software dealing with the mechanics of interfacing the physical input/output devices is segregated from other software. This is done because the periodicity of change for this software is a function of hardware technology advances and is not related to flow control technology advances.

(b). Applications. This software provides the basic flow control function. It is concerned with the machine-independent business of analysis and decision-making support.

(c). Data Management. As the flow control problem becomes more understood, the types and amounts of data about traffic demand and airport capacity will change dramatically. As experience is gained from system usage statistics, it will be desirable to physically reorganize system data to "fine-tune" response-time. Separate data management software is provided to minimize the impact of these changes upon the flow control application programs.

(d). Control. The flow control system will operate in a multi-programming (interleaved execution), multiprocessing (simultaneous execution) environment. An already-existent operating system will be tailored to perform the required resource-management services. Essentially, this operating system is interrupt-driven and controls memory, processor, and peripheral-device resource management.

b. System Activities

There are four major classes of system activity; data base update, information retrieval, advisory dissemination, and performance evaluation. It should be noted that data base update and information

retrieval will occur simultaneously, but asynchronously, in the automated system. They are independent activities. Advisory dissemination and performance evaluation may occur on a time-sharing basis with other activities, but are definitely dependent activities.

1. Data Base Update. This activity records the demand and capacity data necessary for the data analysis and alternative selection functions. Only data readily available at the current time is to be included in the initial flow control system installation; additional data can best be identified after a period of operational shake-down and careful analysis of system performance during the shake-down period.

2. Information Retrieval. The three subsections that follow; quantification, enumeration, and simulation; describe the man/machine interfacing of the flow controller and the computer complex for decision-making purposes. From a strictly operational point of view, these are the primary activities of the system. It is important, however, to place them in their proper context with the balance of the system, and to understand the impact on the balance of the system of even minor modifications to these activities.

(a). Quantification. In order to assess the severity of a situation, it is necessary to quantify the available data. This involves presenting the magnitude of some parameter; or the count of the elements of some set of things. The initial flow control system will provide the flow controller with the capability to ask the question "how many?".

(b). Enumeration. Determination of the magnitude of expected facility demand may not be sufficient; it is necessary to consider the demand mix as well. The initial flow control system provides several capabilities for listing the components of the answer to a "how many?" question. It enables the flow controller to ask the question "which?".

(c). Simulation. This is probably the most sophisticated automation aid provided to the flow controllers as a result of installation of the initial system. It is in this area that technical advancement is of great interest.

The technical approach chosen was the result of extensive analysis and experimentation. It was felt that the sparsity of information currently available without major change to the ATC system, when coupled with the difficulty in formulating an objective function, made operations research opimization techniques inappropriate. Having made this decision, it was a relatively straight-forward choice to implement an event-driven model of the demand/capacity relationship as it appears to exist when real-time and on-line data inputs are taken into consideration.

3. Advisory Dissemination. Once a flow control strategy has been selected, it must be implemented. The initial flow control system will not provide automated support in this area, but near-term enhancements are planned. Prior to these enhancements being installed, flow controllers will communicate via existing voice and teletype circuits. Flow control advisories will be formatted on paper tape, and routed to appropriate users. The following discusses the planned near-term enhancements.

(a). Notification Formatting. The content of the flow control messages generated by the computer complex for the flow controller are not in the proper format to be used as advisories for the aviation community. Upon receipt of the flow control message containing the implementation data (typically the FAD ground delay instructions), the flow controller will have the capability of editing the message for different users, and inserting the appropriate preamble as required for communications protocol. This editing may utilize the computer power locally resident in the intelligent data terminals at the ATCSCC.

(b). Communications. Upon completion of message formatting, the flow controller will forward the message to the addressee (or distribution list) via the FAA switching center. It is planned that this can be accomplished from the same data terminal on which the flow controller received the original message from the computer.

4. Performance Evaluation. The realization that automation of flow control activities would be an evolutionary process came early. The design approach to the initial flow

control system was to implement a system that would be responsive to change. More important, it must be responsive to change in the proper direction. Change for the sake of change is not improvement, so provisions must be made for a feed-back loop which may be used to refine system operation.

(a). Data Recording. There is a lack of data regarding the flow control problem. With the installation of the initial flow control system on a central computer, air traffic data concerning high-density airports w'll be available as a result of daily operations. The recording of normal message traffic regarding actual arrival and departure information will permit analysis of problem situations as well as reevaluation of forecasting procedures.

(b). Data Reduction and Analysis . Off-line software will be provided in the initial flow control system to provide the necessary input for system enhancement analysis and system performance evaluation.

SUMMARY AND CONCLUSIONS

The basic system being implemented has several areas in need of improvement. In the storage and retrieval of data very limited flexibility has been provided. As the system evolves, new data management software will be provided to allow more complex access mechanisms. Database security and integrity checks will be expanded so that a full set of operator key-in functions will be available. In the reporting of flight status information, the flight plan and cancellation messages will be expanded to cover all flights regardless of origin and destination airports. Further, the flow control system will receive flight progress information. Messages such as boundary crossings, fix crossing, etc., are contemplated.

Flight arrival data will be added to the system in the near future. Two significant things are learned upon receipt of an arrival message; (1) the aircraft has terminated its demand upon ATC facilities, and (2) the time of its arrival enables analysis of its total departure-arrival transaction with the ATC system. This data is vital if the accuracy and modeling algorithms of the present system are to be improved.

The manipulation of the model of the airspace structure will have to be improved so that it can be dynamically accomplished. This will allow the flow controller to improve his representation of the true state of the system. Finally, the functional capacity for advisory message preparation and dissemination needs to be expanded. The flow controller should have the capability of editing the message for different users and addressing it for communication.

In conslusion, this system represents a sound first step in automating the central flow control function. Some basic research remains to be done in the areas of capacity modeling, and flow control strategy selection and modeling algorithms. In the current system it is assumed that the ATC facilities organizations are in the best position to estimate their capacities. Thus, no attempts are made to correlate the capacity with weather or other factors. This area offers a potential for great improvement in the management of the overall flow process and should be given a high priority. In strategy selection, the performance of the overall system should be analyzed to determine the criteria for imposing controls and defining measures of the effectiveness of those controls once imposed. Finally, in the modeling area, the event driven model which treats an airport as a single server queuing mechanism and decouples the arrival and departure process should be examined. Obvious improvements are to model the airports as multiserver, multiqueue processes. Further, the coupling between the arrival and departure process is not well understood and needs further study.

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AUTOMATIC TRAFFIC ADVISORY

AND

RESOLUTION SERVICE

(ATARS)

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BIOGRAPHY

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ABSTRACT

This paper presents a summary description of the overall ATARS Program beginning with an examination of recent mid-air collision data as well as near miss encounter statistics prepared by the FAA and NASA. The role of ATARS as a key element of the FAA's Aircraft Separation Assurance program is then described as is the concept of an automatic traffic advisory and resolution service. A summary of IPC flight test results is provided as the basis for the ATARS developmental efforts. The details of the ATARS developmental program leading to the delivery of a Technical Data Package to the operating services for implementation consideration is then presented. The paper concludes with a summary of progress to date.

INTRODUCTION

The Automatic Traffic Advisory and Resolution Service is a pilot oriented ground-based collision avoidance system based upon the earlier concept of Intermittent Positive Control (IPC). It utilizes surveillance data from the Discrete Address Beacon System (DABS), computes traffic and resolution advisories using a totally automated ground computer system and deliveres these advisories to ATARS equipped aircraft via the DABS data-link.

The principal objective of the ATARS program is to improve the safety of civil aviation by reducing the probability for mid-air collisions and near-miss encounters that might result from:

a. The inability of the VFR (uncontrolled) aircraft using see-and-avoid techniques to maintain safe separation from IFR aircraft in control and transition areas.

b. The inability of the VFR (uncontrolled) aircraft using see-and-avoid techniques to maintain safe separation from other VFR aircraft in controlled and uncontrolled airspace.

c. Aircraft deviations due to pilot error or equipment malfunction.

d. ATC System errors.

e. ATC system hardware/software failures.

ATARS is being developed to provide pilots of ATARS equipped aircraft with a comprehensive traffic advisory service and an effective resolution service. For uncontrolled aircraft, the traffic advisory service will enhance the pilots see-and-avoid capability while the

resolution service will provide separation services not previcusly afforded by the ATC system. In the case of controlled aircraft, ATARS will serve as a separation assurance backup to the ATC system.

MID-AIR COLLISION DATA

Statistics maintained by the National Transportation Safety Board (NTSB) show that mid-air collisions have occurred at the rate of 20-40 per year and have produced 60-70 fatalities annually during the period between 1965 and 1976. Although the number of collisions were rather constant during this period, the number of aircraft operations has been rising steadily. This implies that the number of mid-air collisions per flight hour has been steadily declining. In particular, the number of collisions per million flight hours has decreased from an average of 1.2 to 0.6 over the 12 year period.

A recent sample of the NTSB mid-air collision data covering calendar years 1975 and 1976 is shown in Figure 1. As seen in the figure, half of the mid-airs occurred within 5 miles of an airport and below 3,000 feet while the other half occurred in the en route and terminal airspace. Among the en route and terminal collisions, none occurred when both aircraft were being served by the ATC system and flying in accordance with Instrument Flight Rules (IFR). The four IFR/VFR collisions represent 15% of the mid-airs (none of which involved air carrier aircraft) but were responsible for 45% of the fatalities. Although air carrier aircraft have not been involved in a mid-air collision within the United States since 1972, the potential for many fatalities is high in IFR/VFR collisions, since heavily loaded air carrier aircraft are exposed to this threat in mixed airspace. The VFR/VFR collisions accounted for 85% of the mid-airs and 55% of the fatalities in the en route and terminal airspace.

NEAR MISS ENCOUNTER DATA

The magnitude of the near mid-air collision problem can be quantified to some extent by examining the data bases maintained by the FAA's Flight Standards Service and NASA's Aviation Safety Reporting System (ASRS). The Flight Standards data base contains exclusively near mid-air collision data while the NASA data base contains safety reports on potential aircraft conflicts (that is, events in which there was a perceived problem relating to the risk of airborne collision) as well as other safety hazards. Figure 2 presents a breakdown of the 227 Flight Standard near mid-air collision reports (NMACR) for 1975. It is clear from this Figure that very few of the reports are from pilots flying VFR - probably because no immunity from disciplinary action is granted to pilots who make NMACR through the Flight Standard channels. It is reasonable to assume, therefore, that there is a significant number of near mid-air events which remain unreported by VFR pilots. As seen from Figure 2, the involvement of air carrier aircraft in near mid-air incidents is considerable and is cause for concern. The data indicate rather clearly that air carrier exposure to collision threats in mixed airspace is present even if this exposure has not been reflected in the mid-air collision statistics in recent years.

The NASA Aviation Safety Reporting System includes a waiver of disciplinary action to broaden the base of those participating in the reporting program. During the period April 1976 to September 1977, 4870 safety reports were received which are documented in NASA ASRS

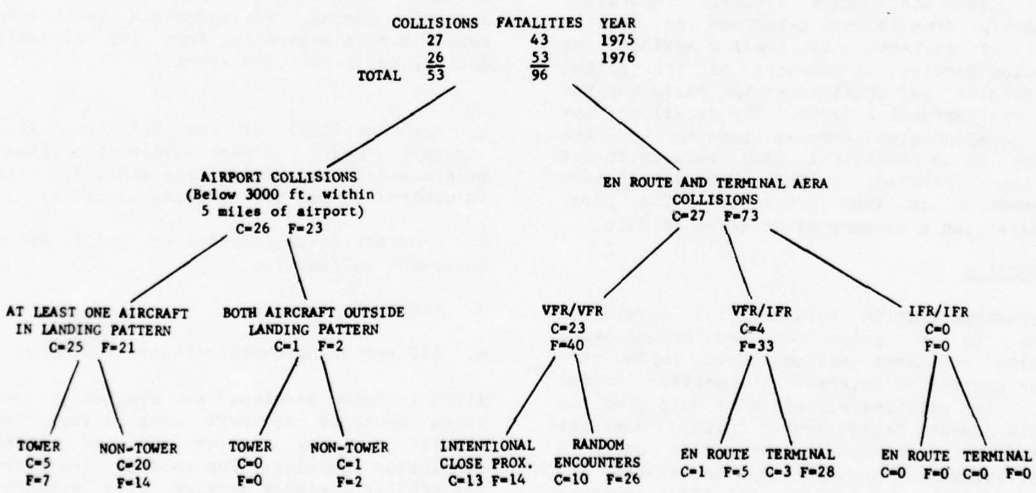
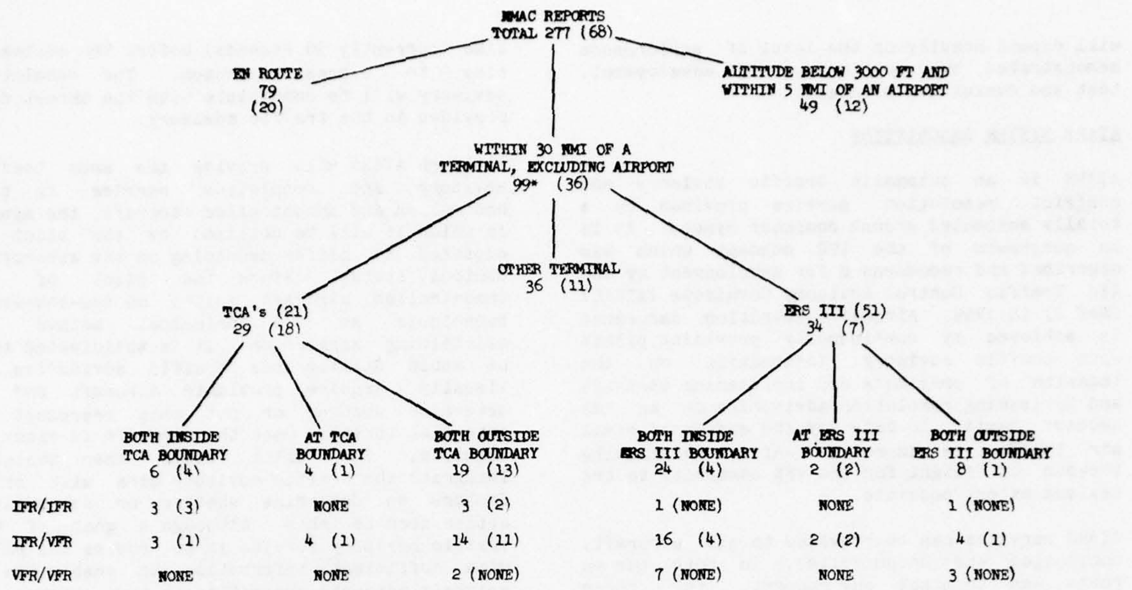


FIGURE 1. MID-AIR COLLISIONS THAT OCCURRED WITHIN THE CONTERMINOUS U.S. 1975-1976.



() AIR CARRIER INVOLVED

FIGURE 2. 1975 FLIGHT STANDARDS NEAR MID-AIR COLLISION REPORTS.

Quarterly Reports. Of these 2108 pertained to aircraft in potential conflict, with 929 reporting miss distances of less than 500 feet. Evasive action was taken by the pilot reporting the incident in 1044 near miss incidents indicating that the pilot judged the potential conflict as a serious encounter. In 136 additional encounters the pilot reported that there was no time for evasive action which would seem to represent a failure of the see-and-avoid process or the ATC system. Further analysis of the serious potential conflicts (that is, those with less than 500 feet miss distance and for which evasive action could not be taken) shows that no type of airspace or ATC control position is immune from the occurrence of these potential conflicts. Of particular note is that 30% of these serious potential conflicts occurred in Positive Control Airspace (PCA) and Terminal Control Areas (TCAs) where all aircraft are controlled.

AIRCRAFT SEPARATION ASSURANCE PROGRAM

In order to preclude a potential deterioration in the safety of civil air travel, the FAA has initiated an Aircraft Separation Assurance (ASA) Program designed to reduce the probability of mid-air collisions and near-miss encounters in all regions of airspace and between all classes of users. Three primary programs that are expected to contribute to the overall objective are being pursued in parallel by SRDS; they are:

a. Conflict Alert/Conflict Resolution

b. Beacon-Based Collision Avoidance System (BCAS)

c. ATARS

Conflict alert/conflict resolution are functions being designed to aid the controller in providing safe separation to controlled aircraft. They will reside in the ATC computer and are intended to reduce the possibility of errors due to a controller oversight and to some extent, pilot error. ATARS and BCAS, on the other hand, are collision avoidance systems primarily designed to aid the pilot in maintaining safe separation.

ATARS will serve as a separation assurance backup to the ATC system in the airspace served by DABS. BCAS (Ref 1), via its active mode, will be able to provide back-up separation services to equipped aircraft outside of DABS coverage where ATARS cannot be provided. For uncontrolled aircraft, the ATARS traffic advisory service will enhance the pilots see-and-avoid capabilities while the resolution service will provide separation services not previously afforded by the ATC system.

Although each of these programs offers some unique capability, there is also some overlap in the functional capabilities for certain classes of users or regions of the airspace. It is expected that implementation decisions will be made in the context of the total ASA Program; moreover, the mix of separation assurance program elements recommended for implementation

will depend heavily on the level of performance demonstrated by each during the development, test and evaluation programs.

ATARS SYSTEM DESCRIPTION

ATARS is an automatic traffic advisory and conflict resolution service provided by a totally automated ground computer system. It is an outgrowth of the IPC concept which was described and recommended for development by the Air Traffic Control Advisory Committee (ATCAC) (Ref 2) in 1969. Aircraft separation assurance is achieved by continuously providing pilots with traffic advisory information on the location of proximate and threatening aircraft and by issuing resolution advisories on an "as needed" basis. In this way the safety of civil air traffic is improved while maintaining freedom of flight for the VFR community to the maximum extent possible.

ATARS services can be provided to all aircraft, controlled and uncontrolled, in both the en route and terminal environment. For those equipped for ATARS services, protection is provided against all aircraft that are equipped with altitude reporting transponders. At present, this represents 100% of the air carrier and military fleets and 17% of the general aviation population. However, with the impending implementation of DABS and with the expected impetus to equip in order to obtain other data-link services, (Ref 3), this percentage is expected to grow significantly over the next two decades. To receive ATARS service, an aircraft must carry a DABS transponder with an altitude encoding capability and an ATARS display. The transponder, in addition to its beacon function, receives digital messages from the ground and delivers them to the ATARS display for presentation to the pilot. The ground portion of the ATARS system consists of the DABS sensor which provides surveillance information and acts as a communications link to the aircraft, a computer which is independent of the ATC computer system, and interfaces to the ATC facilities serving the airspace covered by the DABS sensor.

Aircraft equipped for ATARS service will receive traffic advisories regarding aircraft that are determined by the algorithm to be proximate or to constitute a potential threat. In the case of a proximate aircraft, information will be displayed to alert the pilot concerning the presence of the nearby aircraft and to aid him in visual acquisition. When an aircraft poses a threat, the traffic advisory service will declare it as a potential threat and display additional information to aid the pilot in threat assessment. The threat data should enable the pilot to evaluate the potential threat and to avoid maneuvers which would aggravate the situation. If the aircraft separation continues to narrow such that the projected miss distance is less than the established threshold for that region of airspace, then one or both of the aircraft will receive a resolution advisory at a predetermined time (currently 30 seconds) before the estimated time to closest approach. The resolution advisory will be compatible with the threat data provided in the traffic advisory.

Although ATARS will provide the same traffic advisory and resolution service to both controlled and uncontrolled aircraft, the manner in which it will be utilized by the pilot is expected to differ depending on the aircraft's control status. Since the pilot of the uncontrolled aircraft relies on see-and-avoid techniques as the principal method of maintaining separation, it is anticipated that he would utilize the traffic advisories to visually acquire proximate aircraft and to determine whether or not they represent a potential threat. Once the aircraft is visually acquired, the pilot could then mentally integrate the traffic advisory data with other factors to determine whether or not evasive action need be taken. Although a goal of the traffic advisory service is to provide the pilot with sufficient information to enable him to maintain adequate separation in the absence of visual acquisition, the pilot may choose to delay evasive action until receipt of a resolution advisory if the threat aircraft is not visually acquired. In this way the traffic advisory service would provide increased air safety by reducing the potential for mid-air collisions which may result from undetected traffic or optical illusions without imposing constraints on the pilot. The basic premise is that once the VFR pilot is made aware of a potential encounter and provided data concering the threatening aircraft, the pilot can maintain adequate separation on his own.

In order to minimize pilot work load and ATC interaction, it is anticipated that controlled aircraft will rely more heavily on the resolution advisories rather than on the traffic advisories for determining the maneuver needed to resolve potential conflicts. In these cases the traffic advisories would serve as a means for alerting the pilot to the details of the potential conflict and would prepare the pilot for the possibility of an escape maneuver if the conflict situation persists or worsens. Alerting the pilot to the specifics of the potential conflict would also serve to discourage independent maneuvers on the part of the pilot which could aggravate the situation.

Whenever a threat advisory is issued to a controlled aircraft, an ATARS threat notice message, which identifies the pair of aircraft in potential conflict, is sent to ATC facility responsible for the aircraft. This threat notice may or may not result in an alert being generated for the responsible controller(s) depending on the option selected for interfacing ATARS with the Conflict Alert/Conflict Resolution function. An ATARS resolution notice message will be sent to the serving ATC facility at the same time that the resolution advisory is sent to the aircraft in conflict. The resolution notice message will identify the aircraft involved and the resolution advisories

issued to each. Upon receipt, the ATC computer system will display this data to the responsible controllers.

TECHNICAL APPROACH

The technical approach being pursued in the ATARS program is to develop a traffic advisory service and a resolution service in parallel and then to interface them to achieve operational compatability. The development process for each includes the following steps:

a. Concept development

b. Algorithm development

c. Performance evaluation via fast-time simulation

d. ATC compatibility evaluation via real-time and fast-time simulation

e. Coding logic into DABS/ATARS Engineering Model (EM) Computers

f. Flight testing to determine performance and user acceptance

g. Pre-operational trial and demonstrations

h. TDP preparation

The traffic advisory service will be developed by M.I.T. Lincoln Laboratory based upon the results of the flight tests of the IPC/Proximity Warning Indicator (PWI) function conducted at the DABS Experimental Facility (DABSEF) at Lincoln Laboratory. MITRE/METREK Corporation, developer of the orignal IPC algorithm, will redesign/improve the resolution algorithm to correct deficiencies discovered during flight testing and ATC simulations at NAFEC.

In addition during the developmental process, the ATARS logic will be modified to demonstrate the capability of ATARS to perform additional functions such as terrain avoidance and restricted airspace avoidance. This latter capability could be used to keep uncontrolled aircraft out of Terminal Control Areas (TCAs) and Positive Control Airspace (PCA).

IPC FLIGHT TEST RESULTS

The flight tests conducted by M.I.T. Lincoln Laboratory at DABSEF had two principal objectives: 1) to characterize the performance of the IPC computer algorithms, and 2) to determine the manner in which pilots were able to utilize the services provided by the IPC system. The test results (Ref. 4) validated the feasibility of providing ground-based collision avoidance in conjunction with a single-site DABS sensor, but also identified some significant deficiencies in the resolution algorithm tested.

From October 1974 to February 1977, 130 flight missions were flown. These one hour missions were of three different types: validation (60 missions), demonstration (26 missions) and subject pilot (44 missions). The validation flights were flown with test pilots to characterize the behavior of the initial IPC algorithm and to check out modifications as they were added. Demonstration flights were flown to allow visitors to see IPC in action. Subject pilot flights were flown to allow testing of the IPC-to-pilot interface. This latter test was conducted using a test pilot flying an interceptor and a general aviation (subject) pilot accompanied by a test pilot flying the drone. The subject pilots were drawn from various sources including a list of pilots that previously had been involved in a simulation study of PWI. Some of these pilots were air carrier or military professionals who flew general aviation aircraft for pleasure. The aircraft used in these flights were either a Cherokee Six or a Beech Bonanza F-33 as the interceptor and a Cherokee 180 or Cessna 172 as the drone.

The flight tests indicated that IPC consistently detected and resolved encounters when the encounters involved two aircraft of similar speed in non-accelerating flight with pilots responsive to IPC commands. Incomplete or improper resolutions could occur when any of these conditions were violated. IPC also permitted additional conflicts to occur in some cases when a return to course maneuver was executed by a pilot after successful resolution of the initial encounter.

The PWI portion of IPC was determined to be beneficial as an aid in intruder acquisition. In general, subject pilots reacted favorably to this portion of IPC service. Some of the subject pilots flew missions where only the PWI service was provided. This allowed evaluation of pilot techniques for collision avoidance and pointed up some areas for consideration. Of prime importance is the amount of information provided by PWI. The tests indicated that unless the pilot visually acquired the traffic indicated on the display, he would eventually feel obliged to make a maneuver. The pilot based his maneuver on the PWI information provided; the clock position and the coarse altitude bins. Using this information alone can result in maneuvers that can create a conflict situation that is more dangerous and difficult to resolve than the original encounter.

The resolution or command service of IPC, although consistently effective in nominal encounters, was shown to produce unnecessary, late, or improper commands in situations involving non-nominal (accelerating, etc.) conflicts. Also, when pilots had visually acquired and analyzed the approach of the traffic indicated by PWI, they were sometimes unwilling to follow IPC generated commands because they viewed them as unsafe or unnecessary. Pilots objected when IPC commands forced them to maneuver contrary to the rules of the road or to loose sight of the intruder. These situations indicated that IPC, as then configured, did not consider enough aspects of the encounters to enable proper command

selection. Various factors contributed to improper resolution, including:

a. Uninvolved aircraft close to an ongoing conflict can become involved if they are not properly considered initially.

b. Non-uniform logic can allow conficts to be prolonged or worsened by delaying commands to an IFR aircraft in conflict with a VFR aircraft.

c. No input to command selection logic was provided for turn sensing or rate of turn.

d. IPC selected commands followed fixed rules based on the conflict geometry. This aspect of command selection in accelerating conflicts could and did cause IPC to choose improper commands due to the changing conflict geometry.

TRAFFIC ADVISORY SERVICE DEVELOPMENT

The purpose of this portion of the effort is to develop and evaluate a comprehensive automatic traffic advisory service in such a way that it is complementary to and compatable with the resolution service. It is anticipated that the traffic advisory portion of ATARS would find application principally within VFR community.

The objectives of the traffic advisory service are to assist the pilot in:

a. Obtaining visual acquisition of aircraft that are or will be close enough to be of concern.

b. Evaluating whether or not an aircraft represents a threat.

c. Selecting a safe and effective escape maneuver.

d. Maintaining separation in the absence of visual acquisition.

There are two pincipal benefits to a traffic advisory service meeting the above objectives; namely:

a. An effective traffic advisory service would make a significant contribution toward preventing mid-air collisions involving VFR aircraft without restricting freedom of flight.

b. By providing complete traffic advisory data early enough in the development of an encounter, including data to aid in threat assessment, the traffic advisory service would significantly reduce the probability of an aircraft maneuvering in a direction that would aggravate the potential conflict. In this sense, it is complementary to the resolution service.

The traffic advisory service will be a comprehensive yet flexible multi-level service that can be tailored, by means of a cockpit display unit, to meet the needs of various user groups. It will be able to support a variety of displays ranging from a low cost general aviation display to a sophisticated air carrier display. It is essential to the success of the program that the traffic advisory service be implementable by a low cost display in order to keep it within the economic reach of the VFR community. During the development program, the traffic advisory service will be demonstrated using two or preferrably three levels of display capability. The GA display version will be a low cost alpha-numeric-symbolic display using lights and numerics (LEDs) while the air carrier version will utilize a multi-color Cathode Ray Tube (CRT) with graphic capability.

This multi-level approach will enable the traffic advisory service to provide an effective service to different classes of users which is commensurate with their needs and cost limitations. The information displayed will vary in sophisticaton depending on the cost and type of display used. Some typical information types being considered are range, heading, bearing, altitude, A/C status (IFR/VFR, Equipped/Unequipped) and miss distance (magnitude and direction). It is intended that the manufacturers and users will specify the final display formats and faceplates based upon the results of user evaluations and cost considerations. The scope of the development program is to determine the informantion set(s) and the corresponding formats to be used on the DABS data-link.

A general purpose microprocessor-based display will be developed as the basic vehicle for evaluating the display types selected. The most sophisticated display concept will be evaluated first since it presents the most complete set of information and therefore controls the design of the DABS data link formats. Evaluation of subsequent display concepts will be accomplished by reprogramming the microprocessor and changing the display faceplate as necessary.

A candidate general aviation display could give the pilot bearing information symbolically (clock lights), with heading, range, altitude and aircraft status shown in alphanumerics. A candidate CRT air carrier display is illustrated in Figure 3. This display is known as the "Relative Motion Display" and indicates all nearby aircraft by vector symbols with alphanumeric tags. The center display symbol represents the subject aircraft. A typical scenario is as follows:

a. Upon entering the projection area, the proximate aircraft's position will be projected on the subject aircraft's CRT screen as a vector symbol denoting heading and relative speed. Additional information such as altitude and possibly ID would be given in an associated data block. Range rings would also be displayed on the screen to enable the range of the target to be determined.

b. If this intruder aircraft should create a conflict situation then the data block will begin flashing and a line of projection will extend from the intruder's symbol to indicate

the projected relative motion from which the point and time to closest approach can be estimated.

This dynamic display provides the optimum amount of information to the air carrier pilot and can provide detailed data on several targets simultaneously.

In order for a traffic advisory to be sent to an aircraft, several parameters have to be satisfied. These parameters are based on both distance and time. For the non-potential conflict situations, proximity advisories are sent on aircraft located within a pre-computed range. This range is principally based on the velocity of both aircraft. When one aircraft flies into the protection area of another aircraft, the traffic advisory information is computed for and sent to both aircraft. Aircraft are considered to be in potential conflict when the following parameters are satisfied:

a. The estimated time to closest approach is less than 45 seconds, and

b. The estimated horizontal miss distance is less than 1 n.mi. or the estimated vertical separation at closest approach is less than 1,000 feet.

When these parameters are satisfied, a threat advisory will be issued to indicate the increased severity of the situation. It should be noted, however, the above parameters will be optimized during development and therefore are subject to change.

The ATAS data-link formats used to support the range of display types have not yet been specified. Depending on future DABS data-link requirements and the capacity of the data-link, one or more ATAS data-link formatting procedures will be used. For reasons of simplicity a universal format is desirable. This would assure all users that the quality of information received is uniform. Since the relative motion display may require two or more Comm-A or Extended Length uplink data messages per aircraft contained in the advisory, the use of the universal format may create an unusually heavy load on the DABS data-link. If this is the case, then it may be more desirable to have two types of data-link formats, one for the simpler GA display and another for the more sophisticated air carrier version.

The principal activities involved in the traffic advisory service development are discussed below. The concept definition effort will be based upon the body of knowledge gained during the extensive flight testing of the initial IPC/PWI algorithm. It will include a determination of the following:

a. What basic information must be provided to the pilot to accomplish the stated objectives?

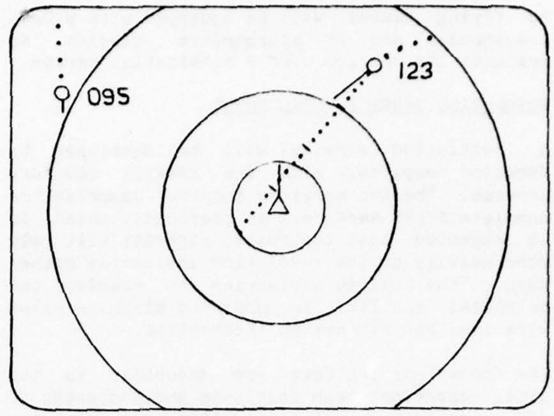


FIGURE 3. A CANDIDATE RELATIVE MOTION DISPLAY.

b. What precision is required in the information provided?

c. What combinations of data and display techniques should be considered?

d. What criteria should be used for displaying a traffic advisory?

e. How will the urgency of the situation be conveyed to the pilot?

f. How will multiple advisories be handled?

g. What is the concept for providing the advisory data via the DABS data-link?

h. Does the traffic advisory service have any impact on the ATC system or procedures?

i. How will the traffic advisory service be compatible with and complement the resolution service?

Following definition of the traffic advisory service, the candidate display concepts will be subjected to preliminary evaluation by pilots to determine the utility of the traffic advisory data being presented as well as the method of displaying the information. As soon as the microprocessor based display becomes available, the display concepts will be subjected to limited flight tests at DABSEF to validate and refine the concepts prior to finalizing the logic and data-link formats. The algorithm will then be coded for retrofit into the DABS/ATARS engineering model at NAFEC. Test and evaluation of the traffic advisory service will begin following check-out of the retrofit.

Pre-operational user evaluations of the traffic advisory service will be conducted in the Philadelphia terminal environment using the DABS sensor located at Clementon, New Jersey. A number of aircraft that are used on a regular basis in the Philadelphia area (such as commuter airlines and general aviation aircraft belonging

to flying clubs) will be equipped with a DABS transponder and an appropriate display to evaluate the service over a substantial period.

RESOLUTION SERVICE DEVELOPMENT

A resolution service will be developed to function compatibly with the traffic advisory service. The two services together comprise the complete ATARS service. As previously noted, it is expected that controlled aircraft will rely more heavily on the resolution advisories rather than on the traffic advisories to resolve the potential contlict in order to minimize pilot work load and ATC system interaction.

The concept of IPC that was described in the ATCAC report has been developed and subjected to ATC simulation tests at NAFEC and extensive flight testing at DABSEF. The development of the resolution service described herein is designed to eliminate the deficiencies discovered during testing in order to meet the following performance goals:

a. ATARS resolution advisories must be safe

b. ATARS must not disrupt routine air traffic control operations by issuing unnecessary resolution advisories which may cause aircraft to depart from clearances issued by the controller.

c. ATARS must be highly effective in preventing and/or resolving conflicts in all applicable regions of the airspace.

d. Major changes must not be required in ATC procedures in order to make ATARS compatible with the ATC system.

The planned improvements to the IPC resolution algorithm are based upon several sources of data, namely:

a. The extensive flight tests conducted by MIT Lincoln Laboratory at DABSEF.

b. Air traffic control simulation conducted at NAFEC with the Air Traffic Control Simulation Facility (ATCSF).

c. Monte Carlo simulations of the 12 midair collisions provided by the NTSB.

d. Analysis of 11 hours of ARTS III data for ATC interaction.

Detailed analysis of the above data sources have indicated the need for the following major modifications:

a. Develop site adaptation logic to be used in the terminal area to reduce unnecessary ATARS interaction with the ATC system. These changes involve using a uniform logic for both VFR and IFR aircraft and optimizing alarm threshold.

b. Replace the fixed rules approach utilized in the IPC algorithm with an exhaustive search technique to select among the candidate single-plane and multiple-plane maneuvers. For each set of candidate maneuvers, the aircraft pair is flown ahead in fast-time for the purpose of computing statistics such as achievable miss distance. The candidate maneuver sets are then rank ordered considering technical factors such as miss distance as well as user oriented criteria.

c. Develop turn sensing logic to make ATARS more responsive to maneuvers, especially in the terminal area.

d. Develop a domino logic to minimize the probability of resolution advisories causing chain reactions.

e. Develop a multi-aircraft logic for situations when chain reactions would be unavoidable with two aircraft logic.

f. Develop a logic for vertical speed limits and horizontal turn limits.

Following its development, the performance of the improved single-site algorithm will be thoroughly evaluated using Monte Carlo simulation techniques against an "integrated data base" consisting of:

a. Encounters run during the DABSEF flight testing that proved to be problems for the original algorithm.

b. The 12 midair collisions obtained from NTSB data.

c. Other encounters selected to rigorously test the algorithm's capability and shortcomings.

The algorithm will also be thoroughly evaluated to determine the degree of ATC interaction to be expected in each region of the airspace. This is to be accomplished by running the logic in fast-time simulation against a comprehensive cross section of actual traffic samples collected from the en route and terminal facilities.

Following the development and simulation evaluation of the improved resolution algorithm, it will be coded into the DABS EM and subjected to extensive flight testing to determine its capabilities and limitations. The algorithm's ATC compatibility will be evaluated using the en route and terminal ATC facilities at NAFEC in conjunction with the DABS EM and the ATCSF simulating DABS.

The result of the single-site development will be an ATARS algorithm designed to operate without site-to-site coordination. It will be able to provide resolution service in regions of airspace served by a single DABS sensor. In regions served by more than one DABS sensor, resolution service cannot be provided without some form of site-to-site coordination. To provide complete service in regions of overlapping DABS coverage, a multi-site ATARS algorithm will be developed. It will utilize a sector processing logic to minimize the peak

site-to-site communications load. The concept of Through-the-Transponder will also be developed and evaluated as a means of reducing the cost of site-to-site communications.

Following development of the multi-site ATARS logic, it will be evaluated for performance and compatibility with the ATC system using the three DABS sensor located at NAFEC, Clementon, New Jersey and Elwood, New Jersey. The Elwood site, which is an en route long range radar site with a 10 second radar scan, will be modified with a back-to-back antenna to provide an effective scan period of 5 seconds. ATARS development will end with the delivery of the complete ATARS TDP capable of providing effective service in the en route and terminal airspace as well as in the single- and multi-sensor environment.

PROGRESS TO DATE

The traffic advisory service is currently in the concept definition stage The development of the microprocessor based display by Lincoln Labs is also in progress. Both efforts are expected to be completed in order to begin flight tests at NAFEC with the DABS EM in September 1979.

In support of both the traffic advisory service development and the resolution service development, MITRE/METREK has developed a software capability to read and analyze ARTS tapes which contain target reports on all Mode C aircraft (both controlled and uncontrolled) within range of the terminal radar. They are currently analyzing traffic tapes from the ARTS III terminal facilities located at Washington. Philadelphia and Los Angeles for information concerning the frequency of traffic and resolution advisories as a function of system design parameters. During FY-79 this effort will be expanded to include other terminals as well as traffic tapes of the en route airspace.

The development of an improved resolution algorithm by MITRE is nearing completion. Beginning in FY-79, it will be subjected to extensive fast-time and real-time simulation to validate the design prior to proceding with an extensive flight test program. The portion of the improved logic relating to ATC interaction is complete and has been tested at NAFEC using ATCSF. The results (Ref. 5) are being documented as of this writing.

The logic improvements that were implemented for the simulation included the uniform logic (logic that treats IFR and VFR aircraft in a similar fashion) and the site adaptation logic. The Chicago Terminal environment with parallel runways was realistically simulated with a representative traffic load ranging from 84 to 99 operations per hour. Three operating scenarios were run for four hours each with six controllers controlling traffic in accordance with procedures characteristic of the Chicago terminal environment. The operating scenarios utilized were the high density all arrival case in IFR conditions, mixed arrivals/departures under IFR conditions and mixed arrivals/departures under VFR weather conditions. In the 12 hours of simulations, seven air traffic control interactions in the form of ATARS threat notices (previously called the controller alerts) were observed while only nine ATARS threat advisories (previously know as FPWIs) and five ATARS resolution advisories (IPC commands) were recorded. This is in contrast to previous ATCSF simulations (Ref. 6) conducted in 1975 using the original IPC algorithm that recorded 119 ATARS threat notices, 142 ATARS threat advisories and 69 resolution advisories during 12 hours of simulation under similar conditions. Moreover, no controller or pilot interactions were observed during the eight hours of simulations under IFR conditions.

The site adaptation techniques developed for the Chicago terminal environment are currently being refined and extended for application in other terminal environments. This logic will be evaluated in the ATCSF during the Summer of 1978 using a realistic Philadelphia traffic sample including the VFR traffic generated by five satellite airports in close proximity of the TCA.

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BEACON COLLISION AVOIDANCE SYSTEM (BCAS)

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Biography

Mr. McIntire is Chief of the BCAS Design Section. Aircraft Separation Assurance Branch, Communications Division. He received his BSEE in 1948 and BSADME in 1949 from Tri-State College. He worked as an engineering leader with Hazeltine, Corportation in Indianapolis, Indiana during a break in employment with the FAA. Mr. McIntire joined the CAA in 1951.

ABSTRACT

The Beacon Collision Avoidance System (BCAS) is an airborne collision avoidance system offering separation assurance and data link services among equipped aircraft. Advanced features of the Discrete Address Beacon System (DABS) are used in the BCAS design to achieve surveillance of intruder aircraft and data-linking to communicate air-to-air and air-to-ground. The principal objective of the BCAS program is to enhance the safety of air travel by reducing the potential for mid-air collisions. It will be compatible with the primary means of aircraft separation - the ground based ATC system.

BCAS is being developed in two stages. The first stage of development will produce an interim system of limited capacity that will issue vertical collision avoidance commands to the pilot. The second stage of development will provide a high capacity system that will enhance the pilots "see-and-avoid", and adds the flexibility of horizontal maneuvers. The BCAS program will be complete with the issuance of a BCAS National Standard.

A. INTRODUCTION

The Beacon Collision Avoidance System (BCAS) is an airborne collision avoidance system offering separation assurance and data link services among equipped aircraft. BCAS is a cooperative system that capitalizes on aviations large investment in secondary surveillance radar (SSR) transponders to achieve effective separation assurance with the very first BCAS installation. Advanced features of the Discrete Address Beacon System (DABS) are utilized in the BCAS to achieve resolution of potential collisions with both the intruder and Air Traffic Control (ATC).

The principal objecti:e of the BCAS program is to enhance the safety of air travel by reducing the potential for mid-air collisions. Supplemental protection will be afforded aircraft operating inside coverage of the ground based ATC system, where Automatic Traffic Advisory and Resolution Service (ATARS) is not in operation; and primary protection to aircraft outside ATC system coverage. At the same time, it will be compatible with the primary means of aircraft separation - the ground based ATC system.

Two BCAS systems are under development. One system is a low development risk BCAS that operates in low to medium density traffic and provides vertical maneuver commands to the pilot. The second BCAS is a more complex system capable of operation in high density traffic and enhances the pilots ability to operate in the "see-and-avoid" environment. In addition, the flexibility of horizontal maneuvers are available.

Based on these requirements BCAS must:

Be compatible with operation of

ATCRBS,

DABS,

ATARS and the

ATC system.

Function during transition from

ATCRBS to DABS operation.

Interface and Coordinate with

ATC and

ATARS.

A final human factors constraint on BCAS is that it must be acceptable to the pilot as well as compatible with ATC. This means that BCAS must be capable of providing safe separation while maintaining a false alarm rate which is equivalent to or lower than ATARS or conflict alert.

B. - BCAS SYSTEM DESCRIPTION.

The Beacon-based Collision avoidance system (BCAS) is a concept (see Figure B1) for an

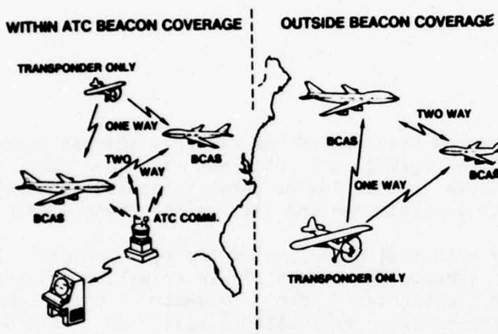


FIGURE B-1

airborne Collision Avoidance System (CAS) based on the use of replies transmitted by the Air Traffic Control Radar Beacon System (ATCRBS) transponders or the furture Discrete Address Beacon System (DABS) transponder.

Two phases of development will provide an interim BCAS which operates actively in the ATCRBS and DABS environment, and a full system that operates actively and passively in an ATCRBS or DABS environment. Two basic modes of operation with several additional refinements are contemplated depending on the ground beacon environment. They are the Active mode required for use in areas where no ground beacon coverage exist, the passive mode for use in high density areas with ground beacon coverage and refinements of active and passive as required by the environment.

In the Active mode the BCAS acts as an airborne interrogator, soliciting replies from other transponder equipped aircraft in communication range. The time between interrogation and reply is measured to determine aircraft range. Altitude is determined by decoding the Mode C transponder replies. By differentiating this data, closing range-rate and altitude rate are determined and used to direct vertical escape maneuvers when the threat evaluation logic determines this is required.

Since the Active mode uses an omnidirectional antenna, all ATCRBS transponder equipped aircraft in communication range reply to each interrogation. To reduce the number of replies, and hence the synchronous garble, an adaptation of the side lobe suppression circuitry used by ATCRBS interrogators has been developed. This adaptation is called Whisper-Shout and is a means of grouping targets generally in accordance to their range from the airborne interrogator. Aircraft are first interrogated at a low power level (the whisper), picking up near and very sensitive receiver targets. Once these targets have replied, they are suppressed. During this suppression period, nominally 35 usec, a second interrogation is transmitted at a higher power level to pick up more targets. This procedure is repeated 5 to 7 times, with the last interrogation (the shout) at full power, insuring that all targets have been interrogated. This results in a smaller grouping of targets on each interrogation and should reduce synchronous garble.

In addition to the Whisper-Shout technique, directional antennas are being studied. Such antennas may further reduce synchronous garble thorough directional interrogate and receive functions which limit the processing load to relatively few aircraft. Other advantages also accrue from the use of directional antennas. By using monopulse detection techniques, the relative bearing to other aircraft can be theoretically obtained to within 10 degrees using the antenna now under consideration. Such bearing accuracy would enable the Active mode to provide Proximity Warning Information (PWI). PWI will in some cases permit a pilot to visually acquire other aircraft during VFR weather but will, in any weather, provide an alert that other traffic is near.

The Active mode DABS interrogations are based on the discrete address transmitted via "squitter" messages from DABS equipped aircraft within communications range. Squitter messages are spontaneous - occurring approximately once per second - and, in addition to making the DABS discrete address known to the BCAS interrogators, provide coarse relative altitude information. BCAS equipped aircraft use the squitter altitude report to determine if the target aircraft poses a potential hazard and, if so, then uses the discrete address for the DABS interogation. No other aircraft reply to the discrete interrogation, thereby reducing fruit and garble.

The Active mode will provide range (r), range rate (r) and altitude (z) information and, with a directional antenna, will provide approximate relative bearing information. Thus, the Active mode can provide PWI capability and vertical escape maneuver data.

In the Passive mode, the BCAS "listens" to ground interrogations and the subsequent airborne replies, and thus does not contribute fruit or garble to the environment. In addition, BCAS obtains as a minimum: (1) the interrogation repetition frequency of the ground radar site, and (2) the bearing of the ground radar site relative to the heading of the BCAS equipped aircraft. This information can be obtained by BCAS without any modification to the ground radar site using the BCAS phased array antenna. However, it is desirable that radar-based transponders (RBX's) be installed at the ATCRBS site to enable a BCAS aircraft to obtain more accurate ATCRBS site information such as site altitude, more accurate relative bearing, and to determine its range to the ATCRBS site. The RBX presence also allows for a data link interface with ATC.

BCAS cannot always operate passively, even when there is some ground surveillance coverage. BCAS performance can vary dramatically as a function of the relative positions of the ground interrogators, the BCAS aircraft, and the target. Certain passive modes of operation have regions in which the positional errors tend to become unacceptably large. When such singularities occur or when the positional error in the passive mode solution is too large a semi-active mode of BCAS must be employed in order to provide acceptable BCAS performance.

Semi-active means use of data from both the Passive and Active modes of operatin. Thus, BCAS will obtain data actively, passively or semi-actively, depending on the environment. These data can be obtained in an ATCRBS or DABS environment with the total system performance improving as the ATCRBS undergoes a transition to DABS (fruit and garble levels are reduced).

Once potential conflicts have been detected, BCAS issues the appropriate warnings based on its tracking data. When both aircraft are BCAS equipped, the maneuvers are coordinated through the use of the DABS data link. Thus, complementary maneuvers are assured. If the target aircraft is not BCAS equipped, maneuvers are based on the assumption that no change in his present course will occur. An appropriate display for providing the pilot with PWI and maneuver information is at issue.

C. TECHNICAL APPROACH

Introduction

The BCAS is a subprogram within the overall Aircraft Separation Assurance (ASA) program. This ASA program consists principally of three programs: Conflict Alert/Conflict Resolution (CA/CR), the Beacon-Based Collision Avoidance System (BCAS) and the Automatic Traffic Advisory and Resolution Service (ATARS).

Conflict Alert /Conflict Resolution can be viewed as a system designed to aid the controller in providing safe separation to controlled aircraft. It is intended to reduce the possibility of ATC system errors due to a controller oversight.

BCAS and ATARS on the other hand, are collision avoidance systems primarily designed to aid the pilot in maintaining safe separation. Both systems will be able to provide collision avoidance services to equipped aircraft against aircraft that are equipped with altitude reporting transponders. They are being developed as complementary elements of the overall ASA programs. Development of the two systems is proceeding independently; however, there is a coordinated effort where commonality of equipment exists (in particular: airborne transponders, cockpit displays and to a certain extent resolution logic).

Prior Efforts

The current BCAS program evolves from an earlier program to develop an effective Airborne Collision Avoidance System (ACAS). Under the program for Airborne Collision Avoidance and Visual Collision Prevention Systems several independent systems for reducing the midair collision problem were investigated. They ranged from Airborne Pilot Warning Instruments (APWI) to ACAS systems.

These system were rejected as the basis for a National Standard because, when compared to BCAS, it was seen that BCAS had broader coverage, less regulatory impact, lower cost for public passenger protection, possible horizontal maneuvers, and provided immediate protection for an equipped user against all aircraft equipped with an altitude encoding transponder.

Current BCAS Program

The BCAS development program is structured to be accomplished in three phases.

Phase I - Feasibility Demonstration: - The Phase I effort involved two parts. The first part of Phase I was an initial analysis of the BCAS operational environment (e.g., traffic models, peak densities, and ATCRBS/DABS surveillance performance) and ATC operational capability to the degree sufficient to assess the technical performance feasibility of the BCAS (e.g., synchronous garble, multipath, shielding, etc).

The second part of Phase I was the design and fabrication of feasibility models of the BCAS sufficient to independently demonstrate the feasibility of the Active, Passive and Semi-active modes. Efforts under Phase I are essentially complete.

Phase II - Engineering Development: Under Phase II, the feasibility models of the Active and Passive modes fabricated under Phase I are being upgraded to include the functional

capability deemed necessary for the operational BCAS system. In addition, a DABS mode experimental model will be fabricated to assess active operation in a DABS environment.

Three engineering models of the interim active BCAS will be developed under Phase II to assess the DABS compatibility and operation of the system. These units will be developed by Lincoln Laboratory. A U.S. National Standard for Active BCAS will be based on the evaluation results.

The Phase II full BCAS Engineering Model development effort is divided into two tasks: 1) Design Definition, and 2) Development and fabrication of three BCAS engineering models, as described in the BCAS system description.

Phase III - Prototype Development and Operational Tests:

The objective of this phase is to verify the operational suitability of the delivered BCAS around which standards may be written.

Field tests will confirm the utility of the BCAS operation, determine the phenomena that limit performance, and determine the related environment. The tests of the BCAS will involve installation of prototype equipments on operational FAA, military and air carrier aircraft for evaluation in the operational environment.

Progress Report on Program

Phase I Feasibility Demonstration

Phase I BCAS activities were exploratory in nature since the impact of the BCAS and ATC operation on each other was unknown. Meaningful events during this period are shown by the following BCAS chronology.

1968 A PWI utilizing ATCRBS was proposed by industry.

1972 USAF awarded a contract to demonstrate concept feasibility of SSR-CAS technique.

1973 SSR-CAS demonstrated on ground at LaGuardia, New York Airport. FAA suggested that an active mode be added to SSR-CAS.

1974 SSR-CAS demonstrated on Pan Am Building, New York City FAA conducted technical analysis SSR-CAS.

1975 FAA proceeded to develop the Active mode portion of BCAS

1975 Contract awarded for delivery of an Active/Passive (SSR-CAS) BCAS system.

The results of these investigations were promising and indicated the need to proceed with Phase II to obtain more deterministic data as it relates to the separation assurance function.

Phase II Engineerng Development

This phase will develop engineering models of the BCAS system. Included are a host of preliminary analytical efforts to examine, operation of BCAS in the ATC environment, campatibility with the ATC system and acceptability to the pilot. Key studies essential to achieving these general objectives are as follows; (1) The determination of ATC System Compatibility, (2) Determination of ATC Interference, (3) BCAS operation in Synchronous Garble and Fruit (4) Evaluation of Todays ATC Environment and (5) Evaluation of BCAS Performance.

1. The Determination of ATC System Compatibility. ATC Compatibility is primarily a function of the BCAS threat evaluation and maneuver selection logic and is manifested principally in terminal areas where controllers intentionally bring aircraft into close proximity to maximize terminal operations. If the alarm rate is too high, resulting in many unnecessary maneuvers, the system will be unacceptble to the controllers, pilots and passengers. However, the trade-off involved in reducing the alarm rate is reducing the protection provided.

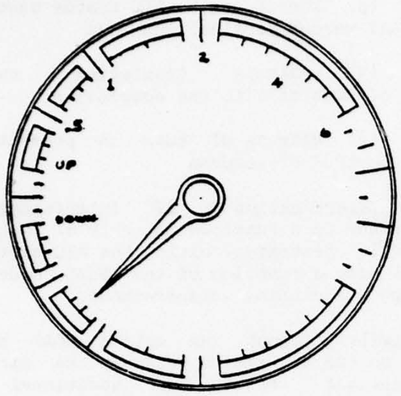
Activity Report - Since 1971, ANTC Report 117 (reference 1) issued by the Air Transport Association of America, has served as the standard for mid-air collision avoidance systems. In regards to those parts of ANTC-117 that deal with threat evaluation and maneuver selection logics there are two questions of concern (1) whether the threat evaluation logics of ANTC-117 provide sufficient time for performing maneuvers necessary to achieve safe separation and (2) whether in dense traffic the expected number of alarm occur infrequently enough for the CAS to be practical. The possibility of modifying the threat-evaluation techniques to achieve safe separation was investigated and found to be feasible.

The threat evaluation techniques for both the interim Active BCAS and the full BCAS are available as a baseline collision avoidance algorithm (Reference 3). The baseline algorithm was structured with flexibility so that it could be used as a point of departure for development of final hazard logic.

The logic contains options to use horizontal positive or negative commands with the passive mode logic, and options for the display of several types of information to the pilot. The display of positive or negative commands can be selected or suppressed. Limit vertical rate commands can be selected for display independently of the selection of positive or

negative commands. Two types of Intruder Position Data (IPD)--flashing IPD's and ordinary IPD's--can be selected for display.

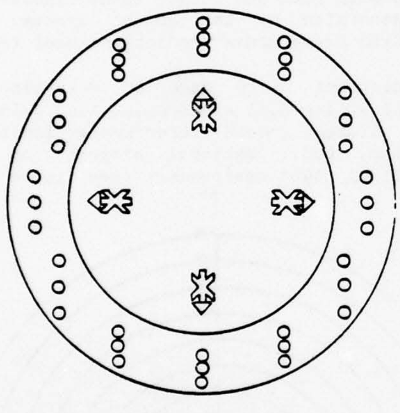
In addition, the logic presented here can drive three types of cockpit displays. The first is the Airborne Collision Avoidance system (ACAS) display which is used with the logic contained in figure C-1 Reference 1. The second



IVSI Display

FIGURE C-1

is the baseline ATARS display described in figure C-2, Reference 2. The third display is a

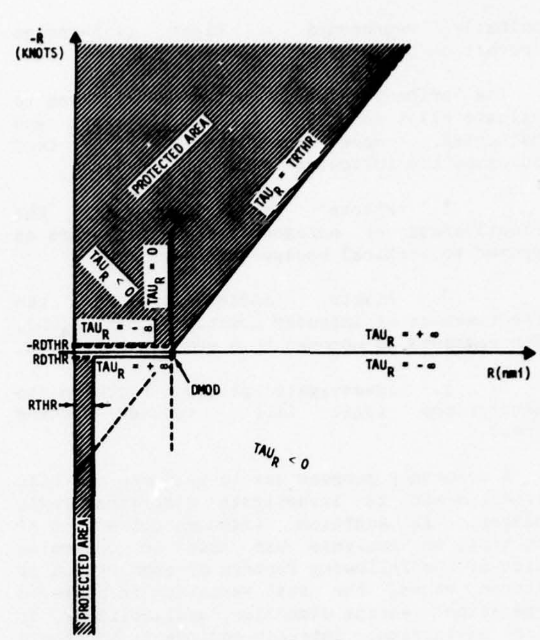


BADCOM Display

FIGURE C-2

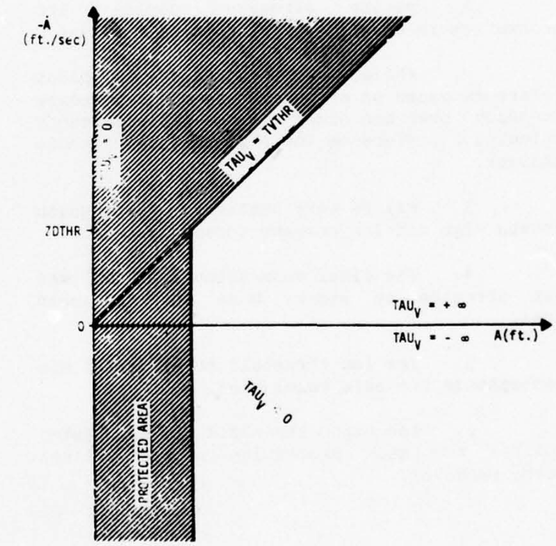
general purpose Plan View Display (PVD) which can present a pictorial plan view of intruder aircraft in the vicinity of the protected aircraft in an own-aircraft-centered and own-heading--oriented framework.

An important characteristic of the detection and resolution logic is that most of the parameters are variable as shown by figure C-3 and C-4 and are determined by own aircraft's location and by intruder's equippage. The process of setting the thresholds as a function of own aircraft's location is refered to as desensitization. The level of desensitization can be controlled by the ground air traffic control (ATC) system or it can de determined by



PROTECTION AFFORDED BY THE DETECTION LOGIC IN THE RELATIVE RANGE – RELATIVE RANGE RATE (R-Ṙ) PLANE

FIGURE C-3



PROTECTION AFFORDED BY THE DETECTION LOGIC IN THE RELATIVE ALTITUDE – RELATIVE ALTITUDE RATE (A-Ȧ) PLANE

FIGURE C-4

the BCAS logic itself.

The initial simulation of the skeletal logic was performed with a GAT-IIA cockpit simulator and the Digital Simulation Facility (DSF) located at NAFEC. The GAT-IIA cockpit simulator

nominally represents a light twin-engine aircraft on the order of a Cessna 310.

The primary purpose of this test was to evaluate pilot reaction to BCAS commands and advisories. More specifically, the test addressed the following areas:

1. Pilots' assessment of the effectiveness of horizonal escape maneuvers as opposed to vertical escape maneuvers.

2. Pilots' assessment of the effectiveness of intruder positional data (IPD), with commands as opposed to a command only mode.

3. Investigate pilots' reaction to desensitized logic (i.e., reduced warning times).

A secondary purpose was to validate the BCAS algorithm and to investigate algorithm logic changes. In addition, although not a part of the test, an analysis was made to determine which of the following factors or combination of factors caused the most variation in achieved separation: escape dimension, availablility of BCAS advisories, intruder equipment, threshold levels, and encounter geometry.

Based on the results of the simulation test (Reference 5), it is concluded that:

1. Pilots strongly desire IPD information in the single intruder environment.

2. While no universal pilot preference based on effectiveness for one escape dimension over the other exists, pilot comments indicated a preference for the vertical escape maneuver.

3. Pilots were unable to distinguish between high and low command threshold levels.

4. The final separation achieved was most affected by escape mode and threshold level.

5. The low threshold level tested was unacceptable for safe resolution.

6. The high threshold level tested provides too much protection for the vertical escape maneuver.

7. The high threshold level provides too much protection for the horizontal maneuver for some geometries.

8. The utility of Vertical Speed Limit (VSL) is derogated by scan-to-scan changes in direction of VSL.

The next phase of simulation will identify and attempt to resolve these operational problems that may exist when BCAS is present in the current ATC system. Those factors which will be studied to determine their contribution to the ATC/BCAS interface problems are:

(1) BCAS alarm rates, nature of and location of alarms in terminal areas

(2) effectiveness of the desensitization levels as described in the algorithm.

(3) impact on the ATC system caused by horizontal versus vertical commands

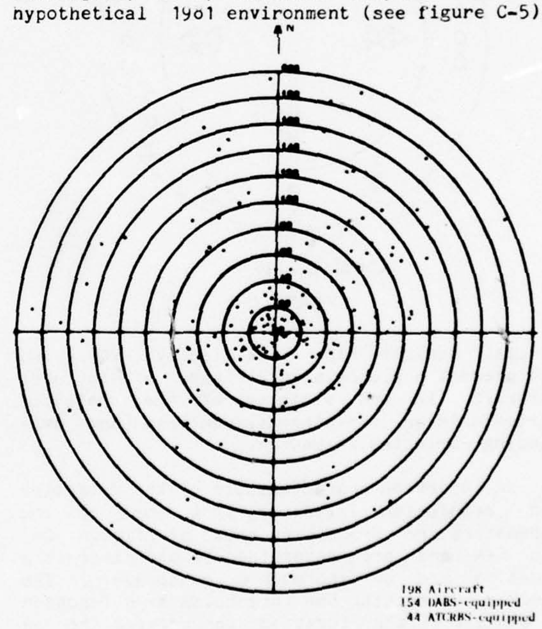
(4) evaluate displaying various options of BCAS data to the controller

(5) effects of BCAS on present air traffic control procedures

2. Determination of ATC Interference. - Interference is a function not only of the fruit and garble generated witin the ATC system by BCAS but also a function of the BCAS modes of operation - including whisper-shout.

Activity Report The active BCAS system impacts on the ATC system because the airborne interrogations result in additional SSR transponder replies and suppressions. To examine the degree of interaction with the ATC system a computer model of the proposed active BCAS was developed (see Reference 6). The model simulates interrogations generated by aircraft equipped with BCAS and merges these signals with those generated by the ground system in a DABS/ATCRBS Performance Prediction Model (PPM).

Predictions were made to determine the impact of active BCAS electromagnetic emissions on the ATCRBS ground interrogator located at Washington, D.C., National Airport for the hypothetical 1981 environment (see figure C-5).



DCA 1981 AIRCRAFT DEPLOYMENT.

FIGURE C-5

Predictions were made for an all-ATCRBS interrogator ground environment and for a mixed environment of 25% DABS sensors and 75% ATCRBS interrogators. Predictions were also made to determine fruit rates at an airborne interrogator and to evaluate the effects of variations in the use of Whisper/Shout in both low-density and high-density environments (see figure C-6).

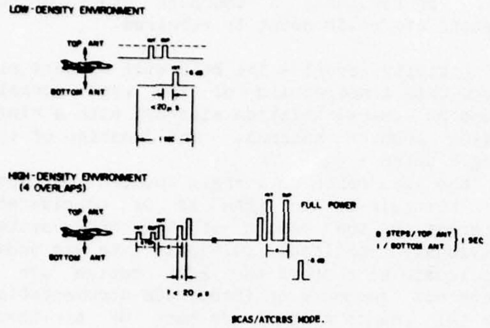


FIGURE C-6

The performance of the ground system is determined with and without BCAS-equipped in the environment. The performance is determined statistically in terms of reply hit-miss histories, target detection and mode A (identitiy) and mode C (altitude) validation. Other interference conditions, such as individual garbles and reply blanking by DABS roll-call fruit, are also investigated.

Based on the predictions, it was determined that deploying active BCAS in the 1981 Washington, D.C. environment will result in a slight reduction in aircrfaft reply probability, but this will not impact the ATCRBS ground receiver/processor performance.

Other predictions showed that instantaneous fruit rates at an airborne BCAS of up to 14,000/sec could be expected at 20,000 feet and that DABS power programming had no effect on BCAS-generated interference in the Washington ATCRBS environment. Work in progress will establish the impact of active BCAS in the Los Angeles, California environment. In addition the effectiveness of BCAS operation will be evaluated in the same Los Angeles ATC environment.

3. BCAS Operation in Synchronous Garble and Fruit. - This is primarily a function of the spacial density of aircraft and the number of ground interrogation sites. It is more of a problem in the active mode, although the passive mode is also adversely affected in the higher density terminal areas.

Activity Report - Garble is the interference experienced by a reply signal when it is overlapped by another reply. When this occurs the altitude code between the framing pulses (F1 and F2) of a reply signal can be altered by the addition or destruction of bits. In fact, garble can cause the loss of a reply signal altogether by interfering with the detection of its framing pulses.

In active BCAS synchronous garble is a direct result of the interrogations transmitted by the threatened equipped aircraft. Aircraft replying to these interrogations are close enough together so that their reply messages overlap. Based on estimates (Reference 9) an aircraft in the center of the 1982 Los Angeles basin can expect 6.3 overlapping replies due to synchronous garble generated at a range of 20 nmi. (This assumes Whisper/Shout is effective in reducing the synchronous garble level by a factor of 1/6 of the peak aircraft density). Garble or overlapping reply messages will also result when the aircraft, in the vicinity of the threatened equipped aircraft, reply to ground radar interrogations and to interrogations from other equipped aircraft.

In passive BCAS synchronous garble is due to aircraft within the main beam of the same SSR as the target intruder, replying to the same interrogations. Interference may occur when a garble reply signal arrives between 20.3 usec earlier and 20.3 usec later than a reply from the target intruder since for such an event the period between the garble reply signal framing pulses overlaps that of the target intruder.

For example (see Reference 10) for the FAA 1982 Los Angeles Basin traffic projection in the most dense regional at the center of the terminal area, at altitudes below 10,000 ft, the density is approximately 0.4 aircraft/nmi^2. At ranges between 20 and 30 nmi from the center of the traffic distribution in the altitude region below 20,000 ft the density is approximately 0.03 aircraft/nmi^2. For an SSR 25 nmi from the BCAS, when the BCAS is at an altitude of 5 000 ft, high density garble volumes of more than 20 nmi and low density garble volumes of more than 40 nmi are possible. In such a case, then, the number of aircraft contributing to synchronous garble could be as large as 8 or more, although in most situations the number would probably be of the order of 1 or 2. When the BCAS is 50 nmi from the SSR, high-density garble volumes of 60 nmi and low-density garble volumes of 120 nmi are possible and the number of aircraft contribution to synchronous garble will be much larger than these estimates. Nevertheless, it is likely that as many as 4 or 5 aircraft will be contributing garble even from some regions of the present day Los Angeles Basin during period of heavy traffic.

Non synchronous garble has been recorded as received fruit rates in a flight from New York to Washington, D.C. (see Reference 11). The fruit was measured as an average rate over a 10-second period. Average fruit rate is computed as the total number of recorded replies (no interrogations) in the 10 second period divided by the total of the listening window times over that 10 second period.

Figure C-6 summarizes a simple model for calculating airborne fruit rates. Note that in

IDEALIZATIONS:

1) REPLY RATE = 150/sec FOR ALL AIRCRAFT

2) TRANSMITTER POWER = 500 w LESS 3 dB CABLING LOSS FOR ALL AIRCRAFT

3) AIRCRAFT ANTENNA GAIN = 0 dB IN ALL CASES

RESULTING FORMULA:

F = 150 × N (30 nmi)

N(R) = NO. OF AIRCRAFT WITHIN RANGE R

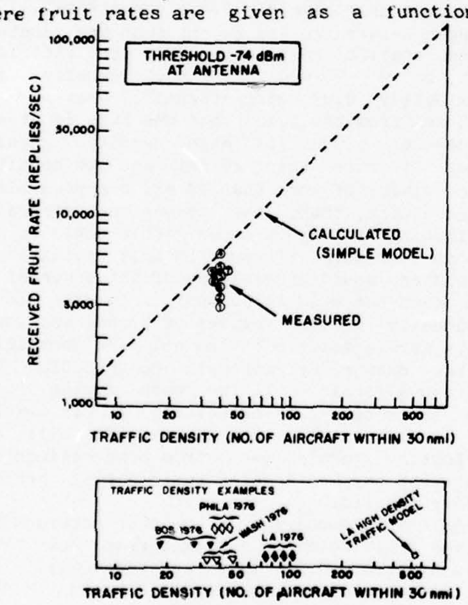
THIS GIVES THE TIME AVERAGE RECEIVED FRUIT RATE COUNTING ALL REPLIES OVER -74 dBm REFERRED TO THE ANTENNA. TO APPLY TO ANY OTHER THRESHOLD, CHANGE THE RANGE FROM 30 nmi BY 2:1 FOR EACH 6 dB CHANGE.

Simplified model for airborne fruit rate.

FIGURE C-7

spite of its simplicity, the model predicts fruit rates as a function of both traffic density and receiver threshold. In fact, the model predicts that fruit rates are a strong function of receiver threshold, increasing by 100% when receiver threshold is reduced by only 3 dB in uniform traffic.

Another form of the simple model vs. measurement comparison is shown in Figure C-8. Here fruit rates are given as a function of



Fruit as a function of traffic.

FIGURE C-8

aircaft density for a fixed receiver threshold (the nominal BCAS value). This type plot relates to the extrapolation into the future of increasing traffic and fruit conditions. The fruit measurements have all been plotted at a traffic density of 40 aircraft within 30 nmi, a value selected to approximate the density along the New York to Washington flight path. Thus the measured values do not themselves indicate a functional dependency, although the model does. To this plot will be added measured fruit rates at higher and lower traffic densities as more data become available.

4. <u>An Evaluation of Todays ATC Environment</u>. To accurately define the necessary BCAS performance, a thorough study of the present ATC environment is required.

<u>Activity Report</u> - The BCAS will operate with the ATCRBS transponders of the type normally found on General Aviation aircraft with a single bottom mounted antenna. The location of this single antenna and

the occurrence of terrain induced multipath on the air-to-air link is of considerable interest in the design of the BCAS system. Previously published multipath data was judged inadequate to support the BCAS design due to incorrect geometry or incomplete documentation. For this reason a study was made of air-to-air multipath based on actual field measurements using a pair of instrumented general aviation aircraft.

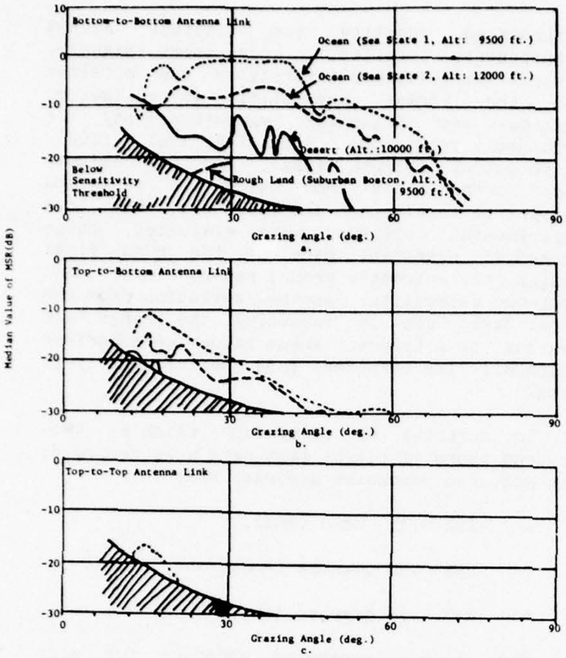
Detectable multipath echos were observed from all reflection surfaces over which measurements were conducted (see Reference 12). Observations were made as to the multipath delay, wavefore, short-term variability, power levels, dependence on geometry, dependence on reflecting surfaces, and the performance of various antenna configurations in rejecting multipath. Data collected over similar surfaces on different days, separated by as much as a year, exhibited striking consistency with regard to each multipath parameter.

The data presented refers to the direct and multipath receptions including the effect of the aircraft antenna patterns. The primary results are summarized in figure C-9.

Results show multipath scattered from smooth surfaces, especially water surfaces, is a significant form of interference on the air-to-air channel. Employment of top-mounted antennas appears to be warranted in preventing strong multipath from interfering with BCAS operation. A single top-mounted antenna in the link appears to provide significant multipath rejection for grazing angles above 10 degrees which includes all geometries of interest in BCAS.

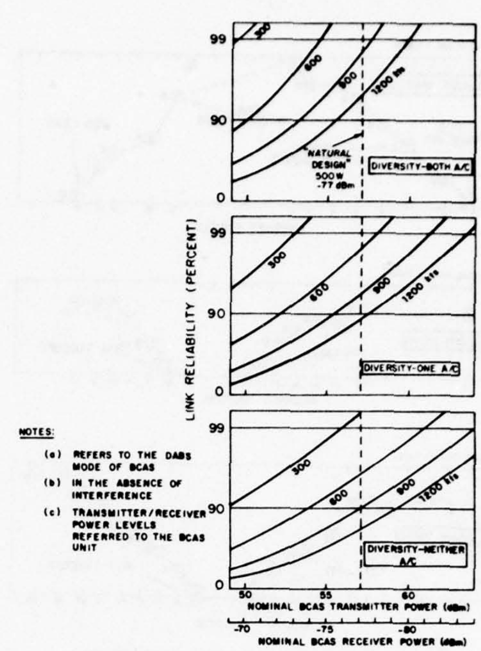
In the design of BCAS power budget there is some freedom in the choice of specifications for BCAS transmitter power and receiver MTL (Minimum Triggering Level). Transmitter power should be high enough to provide adequate link reliability and low enough to prevent interference problems.

In BCAS, very high link reliability at long ranges is probably not necessary What is critical in BCAS is that for any approaching target, detection and threat evaluation be successfully carried out in time to display appropriate warnings and commands to the pilot.



Multipath-to-Signal Ratio Variation With Terrain.

FIGURE C-9



BCAS link reliability vs transmitter/receiver specifications.

FIGURE C-10

(See Reference 14). Thus, there is a strict requirement on a sort of cumulative link reliability and no direct requirement for instantaneous link reliability.

Straight flight situations and turning flight situations each present characteristic problems. In turning flight, aircraft banking tends to increase the likelihood of deep antenna fades; however, since geometries are continually changing, these fades are not long lived.

The study makes use of aircraft antenna gain data resulting from a model measurement program, and is otherwise analytical. It is concluded that appropriate nominal design values (see figure C-10) are transmitter power = 500 watts and receiver MTL = -77 dBm (referred to the BCAS unit). It is shown that these values provide sufficient power margin, at the air-to-air ranges appropriate for BCAS, so as to allow for adverse power deviations that might result from aircraft antenna gains, antenna cabling, and the expected transmitter and receiver deviations due to manufacturing non uniformities and aging.

Uplink (1030 MHz) coverage measurements were made in the Los Angeles Area to examine the level of support for passive BCAS.

Three missions of landings and take-offs were flown in the LA area, one each at the Los Angeles International (LAX), Van Nuys, and San Diego airports (see Reference 13). The missions were intended to answer a number of questions raised in connection with current investigation of passive BCAS:

(1) How many interrogators make up the environment on 1030 MHz;

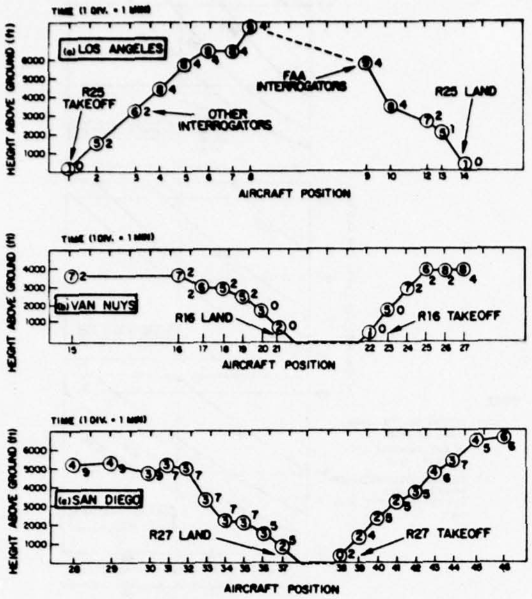
(2) How are these divided between FAA (terminal and en route) and other (mostly military) interrogators;

(3) How does this environment depend on aircraft altitude during normal landings and take-offs; and

(4) What is the power level of the P2 pulses received from each interrogator as a function of altitude, and are enough P2 pulses detectable to allow continuous tracking of the Pulse Repetition Frequencies (PRF's) of the local FAA interrogators.

For each tracked interrogator, the program calculates the PRF, the scan period, the mode interlace, the total number of interrogatins received over a 20-sec period, the peak mainbeam power, and the average angle of arrival of the interrogations (accurate to ±30 deg.). Interrogations outside of the range of fixed PRF's mentioned above, and those with PRF anomalies are not tracked, but are listed by the analysis program.

The measurement indicate a visible interrogator population increasing with height during normal landings and take-offs at the three selected LA area airports (see Figure C-12). The number of FAA and other interrogators visible to the AMF increases rapidly with aircraft height and then tends to become constant above an altitude of approximately



Number of interrogators tracked during landings and take-offs vs altitude.

FIGURE C-11

3,000 ft. The actual number of interrogators seen and the FAA/other ratio are area dependent.

The behavior of FAA interrogators is generally predictable from the ECAC Interrogator File for the area, but other interrogators are either on or off according to time of day and day of the week, and a significant number of interrogators not included in the ECAC file are generally received. Although the total number of received interrogators is not exactly a linear function of altitude, a linear function does provide a first-order approximation for altitudes up to about 6,000 ft., where the rate is 2.5 interrogators per 1,000 ft. for LAX and San Diego, and 3 interrogators per 1,000 ft. for Van Nuys.

5 An Evaluation of BCAS Performance. The ability of BCAS to function in any given environment is influenced by a variety of factors, from fruit and garble to the algorithms selected for BCAS operaion. Simulations are being made of BCAS in varying levels of traffic density.

Activity Report - Evalution of passive BCAS techniques are in progress using an experimental hardware and software design. Extensive flight test provided technical performance data under a variety of parametric conditons. The test flights included flight encounters between two BCAS - equipped FAA aircraft, and also flights against a fixed target and a against targets of opportunity. Reported data is from flight tests completed December, 1975 (see Reference 16).

The passive BCAS measurements were intercepted ground interrogtion signals and intercepeted identity and altitude ATCRBS transponders replies. From these signals, aircraft surveillance information was obtained and the threat possibility is evaluated. Vertical and horizontal maneuvers may be provided from the Time-of-Arrival (TOA), Differential Azimuth (DAZ), and Own Azimuth (OAZ) measurements from which the range and bearing to an aircraft are computerd. Only two experimental systems were evaluated, these lacked an essential part of the BCAS final design, the automatic ground radar selection and lock-on capability. Another deviation from the final design was in computing the range and bearing to a target. These values were derived using off-line computers from the inflight test data.

In a total of fifty-four flights, two-hundred hours of flight test data were recorded. The measured parameter accuracy was;

a. TOA .15 usec (RMS),

b. DAZ .30 degrees (RMS), and

c. OAZ .25 degrees (RMS).

The derived parameter accuracy for good configurations are:

a. Bearing .3 degrees (RMS)

b. Range to Target 300 feet (RMS)

c. Range to Radar 3,000 feet (RMS)

The accuracy of the BCAS measurements was assessed by measuring TOA's and DAZ's during a series of flights past the fixed transponder and simultaneously tracking the BCAS aircraft with the EAIR precision radar, as well as with the ARTS III system. The TOA and DAZ values measured by BCAS were then compared with predicted values based on the geometric relationship of the radar, target transponder (determined by survey) and BCAS postion (measured by the EAIR radar). The measured values of TOA, DAZ, and OAZ were also used to compute the range and bearing to the target.

Analyzes have been performed for the static case and algorithms have been developed to enable computation of range and bearing to potential threat aircraft and to ground radars, using passive-mode BCAS measurements. Only the static solutions are presented. These are solutions based on the differential time of arrival (TOA), differential azimuth (DAZ) and, where appropriate, own azimuth (OAZ) measurements taken at one instant for the configuration as it exists at that time.

The algorithms compute range and bearing to intruder aircraft and radar on the basis of only the current measurements, making use of no a priori knowledge of either the postions of the aircraft or radars or of any previous measurements. For this reason, the accuracies of the computed postions are likely to be worse

than those that would be obtained by dynamic tracking algorithms which would smooth out the effects of measurement errors over time.

Three different modes of purely passive operation have been simulated. These assume all radars are equipped with azimuth reference signals, none so equipped, and only one radar so equipped available at a given time.

It appears that when no radars are equipped with azimuth references, the target bearing cannot be derived with sufficient accuracy to give good target tracks. This conclusion should be verified by dynamic simulation.

When all radars are equipped with azimuth reference signals, the positions of single targets can be determined. The range of configurations in which the solution is excesively error-sensitive is smaller than for the other cases, but under some circumstance the measurements lead to ambiguities in that two distinct configurations can give rise to the same measurements.

When only one radar has azimuth reference signals, two target aircraft must be observed to make calculations of position based on passive measurements possible. The range of configurations in which the solution is execssively sensitive to measurement error is larger than when all radars have azimuth reference signals; multiple solutions do not occur.

In the good configurations of radars and aircraft, target aircraft positions can be determined to within an RMS error of less than 300 feet, assuming measurement accuracies like those obtained by the experimental BCAS system. Radar positions can be determined much less accurately. Errors range from somewhat less that a mile to several miles in configurations with small differential azimuths. The system with two target aircraft is slightly better.

It is judged that either system - assuming all radars equipped with azimuth reference signals or only one radar within BCAS range so equipped - is technically feasible.

BCAS Active Feasibility Model - Test and evaluation of the feasibility equipment for the active ATCRBS mode of BCAS was performed in a NAFEC airborne test bed (Reference 17). The particular technique investigated sends out, omnidirctionally, a mode c (altitude) interrogation on a one-second cycle, it receives and processes all returns, delivers target information ($R, \dot{R}, Z, \dot{Z}$) to a threat evaluator, and provides resolution maneuvers on an indicator.

The threat evalution and resolution logic was not the primary subject of this T&E program; although modification of a standard logic (Reference 1); was used to demonstrate the display. Instead, the object was to shed light on the ability of the equipment to detect, sort out, and track the many overlapping replies that arrive in response to a single omnidirectional interrogation.

The evalution is based on the results of approximately 100 one-on-one aircraft encounters in which: (1) the ability of BCAS to give a proper maneuvers command was examined, (2) the results of one and one quarter hours of data on targets-of-opportunity in the environment of the Washington D.C. TCA; and (3) an examination of flights with a controlled target aircraft in the airspace near NAFEC to explore the effects of antenna coverage.

It was found that aircraft antenna shielding or multipath, was the major factor affecting the overall tracking performance. Auxillary tests made to localize this fact pointed to the conclusion that synchronous garble and tracker parameters caused relatively little degradation in the Washington airspace as compared to antenna coverage problem. Inspection of the performance as a function of both relative range and relative altitude, provides the results shown in Figure C-12. The most significant trend is that for aircraft within 5 nmi of our BCAS aircraft the performance is much better if they are above us than below us. This bias may be expected, since their transponder antennas are invariably mounted beneath their aircraft. Figure C-12 strongly indicates that antenna shielding is an important factor, however, the impact of multipath on a bottom mounted antenna was not established. Further flight tests to examine the impact of multipath on the active feasibility BCAS were made, however, the data has not been reduced.

RANGE (NMI)

RELATIVE ALTITUDE (K FT.)	0-5	6-10	11-15	
>5	.87	.83	.84	ABOVE
0 TO 5	.97	.90	.66	ABOVE
0 TO -5	.72	.68	.51	BELOW
<-5	.65	.71	.67	BELOW

REGION OF INTEREST IN TERMINAL AREA

a) ASSOCIATION IN 5-NMI INCREMENTS

RANGE (NMI)

0-5	0-10	0-15
.87	.84	.84
.97	.92	.79
.72	.69	.60
.65	.69	.68

b) CUMULATIVE ASSOCIATION

.73	.74	.68

c) CUMULATIVE ASSOCIATION FOR ALL ALTITUDES

NOTE: THE DATA REPRESENTS ABOUT 350 TRACKS.

ASSOCIATION DATA FOR BASIC MODE

FIGURE C-12

Accuracy data is derived from a limited data base and is shown by Table C-1 (see Reference 18). The measured errors in range rate and altitude were about as expected. It should be noted that the accuracy flight test was not run in a vacuum. There were other aircraft on the ground as well as fixed transponders on buildings which generated garble. The existence of several BCAS tracks on the target, at slightly different ranges, and many tracks being successfully extended, indicates the presence of garble and phantom bracket detects. This provided a fortuitous chance to measure BCAS

COMBINED RESULTS (85 SECONDS)

Parameter	Mean Error	rms Error	Standard Deviation	Desired Maximum Bias	Desired Precision (1σ)
Range	128.6 ft	157.5 ft	90.9 ft	350 ft	25 ft
Range Rate	6.9 ft/s	36.9 ft/s	35.8 ft/s	-	53.2 ft/s
Altitude	-9.2 ft	28.4 ft	26.9 ft	106 ft	18 ft
Altitude Rate	-0.26	5.6 ft/s	5.6 ft/s	-	25 ft/s
Own Altitude	-42.2 ft	52.2 ft	34.1 ft	106 ft	18 ft
Own Altitude Rate	-5.6 ft/s	6.8 ft/s	3.9 ft/s	-	25 ft/s

TABLE C-1

accuracy in the presence of some garble.

This active feasibility test bed has been upgraded to included the active DABS mode. Flight tests of the active ATCRBS/DABS BCAS were performed in the Los Angeles, California area, where aircraft density is high. During the first series of testing the Whisper/Shout attenuators (2) failed and after repair a second series of tests were performed in the Los Angeles area Data from both test is being analyzed.

Phase II Planned Activity - Analysis and simulation of ATC interaction with the hazard logic will result in further refinements. The active portion of the algorithm will be supplied to Lincoln Laboratories for application in the design of an active BCAS that operates in with ATCRBS and DABS environments.

The full active/passive hazard algorithm will be provided to the contractor(s) that will design and develop the full BCAS.

The final activity in Phase II will be test and evaluation and preparation of a final report on each of the above systems.

D. SUMMARY

As air traffic in this country has continued to increase, so has the threat of midair collisions. In an attempt to solve or alleviate this problem, the FAA, has been searching for an Airborne Collision Avoidance System (ACAS).

Three ACAS systems were tested by or under FAA auspices. All were cooperative; that is, users who bought such a system would get no protection against aircraft that had not installed similar equipment. This implied mandatory equippage and placed a heavy economic burden on general aviation. Because of this and other problems (international aspects, lack of bearing data, radar altimeter interference), these systems were rejected and it was decided to proceed with a Beacon Collision Avoidance System (BCAS) which alleviates many of these problems.

BCAS is a concept for an airborne collision avoidance system based on the use of replies transmitted by the Air Traffic Control Radar Beacon System (ATCRBS) transponders or the future Discrete Address Beacon System (DABS) transponders. Two basic modes of operation are contemplated, depending on the ground Beacon environment. They are the Active Mode, for use in areas where no ground radar coverage exists and low to medium density environments and the Passive mode, for use in high density areas with ground radar coverage.

BCAS provides supplemental collision protection within ATC system coverage, and primary collision protection outside ATC coverage and capatalizes on present and future avionics investment (domestic and international).

The BCAS program is divided into three development phases:

Phase I Feasibility Determination

- Active BCAS (complete)

- Passive BCAS (complete)

Phase II Engineering Development

- BCAS system design

- Active interim BCAS engineering models

- Active BCAS U.S. National Standard

- Full BCAS engineering models

Phase III Prototype Development and Operational Test

- Full BCAS prototype models

- Operational test

- BCAS U. S. National Standard

APPENDIX E

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DABS DATA LINK APPLICATIONS

DEVELOPMENT PROGRAM

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BIOGRAPHY

John J. Bisaga is a Branch Chief (Acting) and is currently responsible for the definition and conduct of the Discrete Address Beacon System (DABS) Data Link Applications Development Program. He received his B.S. and M.S. in Electrical Engineering in 1955 and 1963, from Drexel University. Before joining the FAA in 1975, he occupied a wide variety of junior and senior engineering research and development positions in industry with responsibilities ranging from component and subsystem design through the design of complete communications and radar systems. Since coming to the FAA as a Section Chief, Mr. Bisaga has worked on the AEROSAT Program and has contributed to the establishment of several communications programs in the FAA.

ABSTRACT

The DABS Data Link Applications Development Program has as its principal objective the development, evaluation and demonstration of the benefits and methods of using the digital data link capability inherent in the signal structure of the DABS sensor to transfer air-ground aviation related messages of many types. The program will define the ground-side interfaces and information sources necessary, the means of formatting the information on the air-ground link and the required pilot or flight crew and controller interactions, if any.

Maximum flexibility will be permitted on the aircraft side so that the user can select from a wide variety of display output techniques which are appropriate to the data link services he desires and the price he can afford.

Current emphasis in the program is the detailed definition and development of a near-term package of services that could be implemented in the same time-frame as the DABS sensors, i.e., the mid 1980's. Work is progressing toward some basic experimentation in November-December 1978, and further services development in the Spring of 1979, both taking place in the DABS Experimental Facility at Lincoln Laboratory. Formal test and evaluation of these near-term service candidates will occur in late calendar 1979, at NAFEC, using the DABS sensors which are currently being installed there.

BACKGROUND

The notion of using an automatic data link to connect the ground ATC automation system and other data sources to the aircraft has captured the imagination of ATC system planners for several decades. As a result of continued user interest, coupled with technology availability, the FAA is launching an R&D program specifically designed to bring data link services into being for a wide variety of users within the next 5 to 7 years.

The introduction of these air-ground data link services is visualized to be evolutionary over a period of years, starting with an early mixture of a limited number of ATC automation, weather delivery and terminal information services provided to both general aviation and air carrier users of the airspace. These will be followed by other enhanced services which will be defined in greater detail as the program progresses.

The objective of the DABS Data Link Applications Development Program is to develop, evaluate, and demonstrate the benefits and methods of using the DABS digital data link capability to provide these services in an evolutionary manner. The program will define the ground-side interfaces and information sources necessary, the means of formatting the information on the air-ground link and the required pilot or flight crew and controller interaction, if any. Maximum flexibility will be permitted on the aircraft side so that a user can select from a wide

variety of display output techniques which are appropriate to the data link services he desires as well as the price he can afford.

The link design will specifically allow for the interface with a full range of avionics. This will give industry wide latitude to innovate and develop low cost avionics for the full spectrum of users. A National Standard will be necessary only to define the services available and how the information is contained in the link transmission.

The initial package of services is being developed to minimize controller and pilot interaction with the data link, and reasonable success has been achieved in the initial designs.

The DABS Data Link Applications Development Program is a recent addition to the RE&D Program. Preliminary work was begun last year when an ad hoc committee was formed in the FAA for the purpose of examining the potential for enhanced safety, productivity, and capacity offered by DABS data link and defining the most promising near term applications. FAA offices which participated included Systems Research and Development Service (SRDS), Office of Systems Engineering Management (OSEM), Air Traffic Service (AAT), Flight Standards Service (AFS), National Aviation Facilities Experimental Center (NAFEC), and the Department's Transportation Systems Center (TSC). The committee developed a comprehensive list of data link services and ranked them according to priority and ease of implementation.

A report of this work is currently in preparation (Reference 1). The work done by the committee demonstrated that sufficient potential existed in the near-term applications to serve as the basis for a research and development program. SRDS initiated a formal program and began writing the associated program plan. Additionally, a data link concept paper was developed to address the longer range implications of data link services. Drafts of these documents are currently being reviewed internally.

The applications identified were subjected to further analysis and review by SRDS, the FAA operating services, potential users of the services, and industry representatives. The near-term services identified for development, demonstration, test and evaluation are discussed in the next section.

The test and demonstration program, together with expanded avionics development, will more fully define the operational aspects of these data link services. This will take place over the next year and lead to formal test and evaluation activity at NAFEC in late 1979. At the same time, the program will study additional enhancement candidates for longer range implementation.

PRODUCTS/EXPECTED RESULTS

Near-Term Data Link Services

Two fundamental criteria were used in selecting the development candidates for the near-term DABS data link test and demonstration program:

a. The services had to have the potential of contributing to the safety, capacity or productivity of the system from the perspective of the operators and users.

b. Each of the services had to be capable of implementation in the near-term (by the mid 1980's).

The implications of the former criteria are obvious: It requires concentration on those aspects of the system where the data link can provide operational improvements. Current operations require human delivery of ATC services, which is often an inefficient use of resources, can contribute to the occurence of system errors, and is sometimes detrimental to the performance of the primary responsibilities of the controller and pilot. Also, the limitations of current equipment often preclude improvements in the service currently being provided.

The major implications of the latter criteria are:

a. Test and Evaluation to support the start of implementation in the mid 1980's is required by the 1979-80 time frame. The end of 1979 is the present goal.

b. The services to be provided must be coordinated with other FAA programs which provide the basic data sources and information sinks.

c. Controller interaction with the data link must be minimal. Optimum controller terminal devices are under development (References 2 and 3), but are not scheduled to be available for test and evaluation in time to support the demonstration program for the near-term services. Longer range enhancement services will be developed to use these new terminal devices.

d. Data link usage of the ground ATC automation capability must be based on current field capability or those enhancements which are well along in development. Future data link services will be designed to include the automation features currently being studied by FAA's advanced planners.

A final point should be made before discussing the services selected as near-term candidates. None of the services can be made available to the airspace users unless they are equipped with DABS transponders and minimum input/output devices. On the other

hand, the users will not be motivated to so equip unless the services are available or are demonstrated to be imminent. Therefore, any program designed to provide high utilization of data link services must be implemented on the ground first, and the necessary standard issued. The innovation by industry necessary to develop the low cost avionics will follow.

The data link services which have been identified as candidates for near-term implementation are:

a. ATARS - (Reference 4)

b. Real-Time Surface Winds - The direction and velocity of airport surface winds are now provided the flight crew by the controller during their initial contact when on approach or departure. However, at times when the winds are variable, a continual update of wind velocity and direction is desirable especially as it exists near the end of the runway. This type of continual information which the controller cannot now provide at busy hubs is important to flight crews to enable them to properly plan the takeoff, approach, and landing especially in low visibility and low ceiling situations.

c. Wind Shear Information - This type of information is presently provided by the controller to the flight crews at Chicago O'Hare International Airport which has the sensors necessary to detect this phenomena. The installation of wind shear detection equipment is presently planned for several large hubs which will provide both the controller and flight crew with this vital information. DABS data link makes possible the provision of this information directly to the flight crew on a continuous basis.

d. Takeoff Clearance Confirmation - Takeoff clearance is presently transmitted from the controller to the flight crew by voice link. This frequently occurs during the time when the flight crew is most occupied. A data linked takeoff clearance confirmation, provided in such a manner that would allow the flight crew to confirm that clearance exists at a glance, would prevent any possibility of misunderstanding between the crew and the controller.

e. Runway Visual Range (RVR) on Final and Prior to Takeoff - The RVR is provided by voice communications from the controller to the flight crew during their initial contact with approach or departure control. It is not always possible for the controller to provide RVR updates precisely when needed by the pilot. The situation is especially critical when the RVR is constantly varying during periods of low visibility. DABS data link can provide accurate, real-time RVR values to the crew during the critical phases of flight to permit them to determine whether a landing or takeoff should be attempted.

f. Minimum Safe Altitude Warning (MSAW) Advisory - In all 63 ARTS-III terminals, the approach controller is provided a warning if the approaching aircraft is in danger of descending below the minimum safe altitude programmed into the computer. The controller must then relay this warning to the flight crew. This warning could be sent directly to the crew as well via data link, thus reducing the delay between detection and warning transmittal. This would possibly lower the look ahead interval and result in a better service.

g. Altitude Assignment Confirmation - During en route phases of flight, changes in altitude are directed to the flight crew by a controller using voice communication. Past occurences of misunderstanding of an altitude assignment or garbled transmission indicate that changes in the present system of altitude assignment must be investigated. Providing a confirmation of the altitude assignment information to the flight crews via data link eliminates the potential errors inherent in the voice system.

h. Selected Routine Weather - Routine weather information such as Surface Observations, Terminal Forecasts and Pilot Reports (PIREPS) are currently provided by voice communication to the flight crews and general aviation pilots. Although it is important that the pilots have access to this information, it must be presented on request only, to avoid cluttering the cockpit with unnecessary data. The Aviation Weather Systems Integration Program (Reference 5) will have a very large weather data base available on line. The delivery of this information on request to the cockpit without controller or flight service specialist involvement not only makes the needed information available to the pilot, but reduces the human workload as well. Hardcopy for future reference can also be obtained easily.

i. Airport Terminal Information Services (ATIS) - ATIS is currently provided by a broadcast voice recording transmitted from the airport. Some of the limitations of the present ATIS are:

(1) A controller or flight service specialist must make the recording from information obtained via instruments whenever conditions change significantly. Besides the human involvement with its inefficiency and potential for error, the broadcast can be out of date for some items, if the responsible individual has a heavy workload.

(2) The line of sight characteristic of VHF transmission and lack of ground information netting limits the range from the airport over which a pilot can receive ATIS.

(3) Because ATIS is a broadcast service, a pilot cannot selectively choose or continuously monitor one or more items of interest and ignore the rest. He must listen to the entire broadcast.

(4) Hardcopy (a record) cannot be obtained easily. If the pilot desires a record, he must write it himself.

(5) The tape recorders currently in use are aging and have been identified as a source of maintenance problems.

To circumvent these problems, a digital ATIS concept is being evolved using the DABS data link for delivery. The concept is not complete at this time but some of its possible features are:

(1) Ability to request and receive a full ATIS report via a ground netting arrangement independent of aircraft location as long as it is within DABS coverage.

(2) Generation of most information items using direct sensor inputs (in many cases the same sensors the human uses to formulate the current broadcast). This not only eliminates the human workload but provides real-time, up-to-date information automatically. The exception item might be runway in operation.

(3) Ability of the pilot to rapidly scan and even jump directly to items of interest in an entire report without reading the entire report.

(4) Ability to make a hard copy.

(5) Ability of the system to selectively filter out items which are not of interest to the pilot and provide those that are of interest depending on phase of flight. For example, if RVR and runway surface winds (as differentiated from the center field monitor winds) are made part of the ATIS report these items might be included in the first report, deleted in the updates, but might be the only items when an aircraft is approaching the final phases of flight. Runway in operation, for example, is certainly of no use at that time.

(6) Ability of the system to provide updated reports automatically, once the pilot has requested an ATIS report, if information items change significantly.

Program Milestones

The program to develop these candidates and further select from among them for early implementation is divided into three phases.

The first involves a period of early demonstration and experimentation in late CY-1979. This experimentation will use a general aviation type aircraft outfitted with a set of experimental avionics (described later in this paper). The ground system will be the DABS Experimental Facility (DABSEF) at Lincoln Laboratory. Appropriate hardware and software modifications will be made to support experimentation with the candidate services. Sensors for runway winds and RVR information will be locted on Hanscom Field. Test flights using a general aviation type aircraft will use that airport. Limited functions of the Applications Processor (AP) (described in the next section) will be implemented in the DABSEF computer. An interface with the flight services weather data base located at MITRE/METREK in McLean, Virginia, will be established to retrieve the weather products to be provided. No ATC automation interfaces will exist, but these functions will be simulated in the DABSEF. The alphanumeric information on the link will be coded using 6 bit truncated ASCII. This is an expedient measure for the time being to permit early experimentation. It is expected that ultimately special encoding of the information will be used to optimize link capacity. The main purpose is to experiment with the candidate services and obtain a first order assessment of their utility and methods of providing the services.

The second phase of development of the candidate services will occur in the spring of 1979 when further work will be done using the DABSEF. A new generation of avionics is expected to be available which will have both alphanumeric and graphics capability (for future services experimentation). High efficiency link information formats will have been developed for the candidate services and will be used with this work phase. A model of the Applications Processor is expected to be available at this time to provide the necessary interfaces. ATC functions will still be simulated in DABSEF software and hardware and Hanscom Field will still be the base of flight operations.

Current plans are to move the program activity to NAFEC for formal test and evaluation of the candidate services sometime during late fall 1979. The DABS equipment currently being installed at NAFEC will be used for this activity. An Applications Processor will provide the necessary interfaces. Appropriate sensors will be installed at NAFEC or existing ones will be used if possible. Test ATC software for the en route and terminal automation interfaces will be available in the System Simulation Facility and the Terminal Automation Test Facility respectively. Aircraft used will include NAFEC test aircraft and hopefully some air carrier and general aviation aircraft. The ouput from this activity will be data to be included in the Technical Data Package which will support possible implementation of the finally selected services starting with the first DABS implementation.

TECHNICAL APPROACH

Air Ground Lin.

The technical approach is to use the air-ground data message delivery and reception capability of the DABS sensor (Reference 6) to provide the fundamental air-ground data link. These messages can be transferred as an integral part of the transaction necessary to obtain surveillance data for aircraft tracking as shown in Figure 1. The aircraft, of course, must be equipped with a DABS transponder and appropriate input/output devices. Output devices could include electronic and/or mechnical devices of many kinds, depending on the type of aircraft and the services desired.

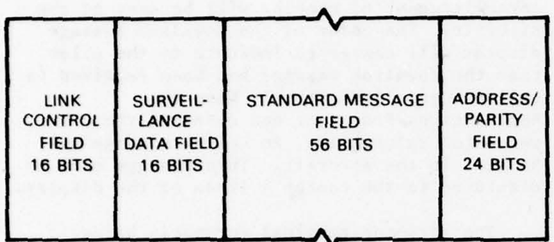

FIGURE 1
DABS NORMAL DATA BLOCK FORMAT

Ground Environment

The DABS sensor has been designed to provide all the necessary data link channel management to ensure accurate delivery of a properly formatted message to an aircraft within its responsibility. Formulating the message, routing of downlink information requests, retrieval of information on request and performing any processing functions dependent on a particular data link service are not the responsibilities of the DABS sensor. Much of the source information is available at the facility (the en route center, the TRACON/tower and the flight service station) and not the DABS site. There is, therefore, a requirement for data link processing capability at the facility.

Figure 2 shows the overall system concept being pursued in simplified form. The DABS site has a surveillance line to each ATC facility over which target tracking reports are sent. This program is not concerned with these lines. In addition, full duplex communication lines will exist between each DABS site and each ATC facility. One line will connect to each of the facility automation computers to provide the ATC message services (MSAW advisory and altitude assignment confirmation). Others will connect to an Applications Processor (AP) at each facility which will perform the necessary functions for all other services, including the ground-ground netting via NADIN (Reference 7). The AP will provide interfaces for all information sources. The information source for the weather services will be the Flight Services Data Processing System (FSDPS) (Reference 5). The AP will make the aircraft look like a Pilot Self Briefing Terminal (PSBT) to the FSDPS. NADIN will be used to connect the AP with the FSDPS.

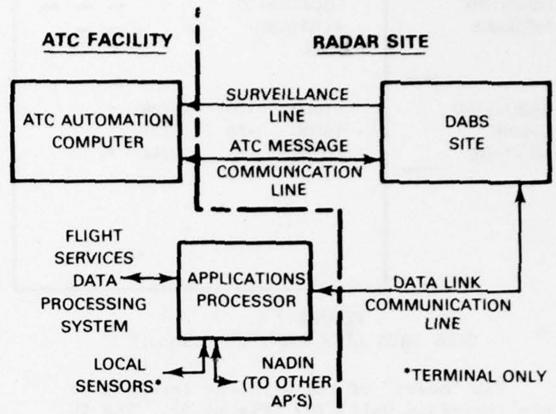

FIGURE 2
SIMPLIFIED DATA LINK SYSTEM CONCEPT
(INITIAL IMPLEMENTATION)

The AP will integrate all the inputs to and formulate the ATIS report and provide the retrieval and delivery capability. Any ground filtering provided will be done in the AP. The AP's at the various facilities will be netted using NADIN. This will provide the availability of remote services and ultimately will permit continuous data link coverage as the aircraft moves from sensor to sensor.

The DABS site contains the logic to handle the multiple inputs and resolve priorities. The ATC messages will be given priority over others.

In the initial implementation for test and evaluation at NAFEC, the two communication lines previously mentioned will be used (one for ATC messages and one for all others). In the enhancement program, the two lines will be reduced to one with the AP providing the multiplexing function as well as any other functions necessary such as code conversion and priority resolution.

Avionics Development

Because of the limited time available for the procurement of the first generation airborne terminal, maximum utilization is being made of off-the-shelf hardware. The first generation terminal uses a color CRT for the split screen display of alphanumeric data (Figure 3) plus an alphanumeric keyboard (Figure 4) with multi-function keys. The top 4 lines x 21 characters of the display will show the downlink message. The middle 4 lines x 32 characters will display the uplink message received as a result of a downlinked

request and the bottom 4 lines x 32 characters will display an unrequested uplink message. A printer will be provided that, when activated via the keyboard, will print the information as displayed on the CRT.

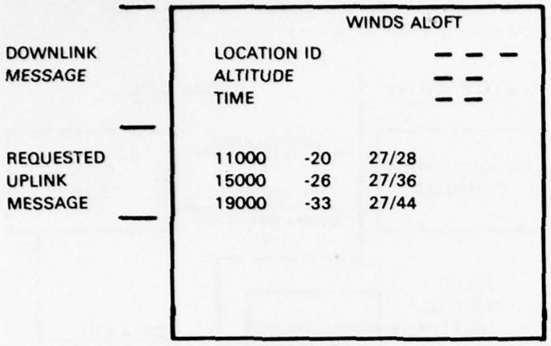

FIGURE 3
DABS DATA LINK AIRBORNE DISPLAY

The "heart" of the airborne terminal is the Interface Unit (IU) (Figure 5). The IU accepts data from the DABS transponder SM interface at 1M bit/sec and formats properly-addressed messages for display on the CRT, or printer. The IU interfaces with the CRT display at 5K bits/sec and provides an RS232C interface at 19.6K bits/sec for the printer. The most recent requested uplink messages is stored in a 4K-bit RAM display memory. Likewise, the most recent unrequested uplink message is stored in another 4K-bit RAM display memory.

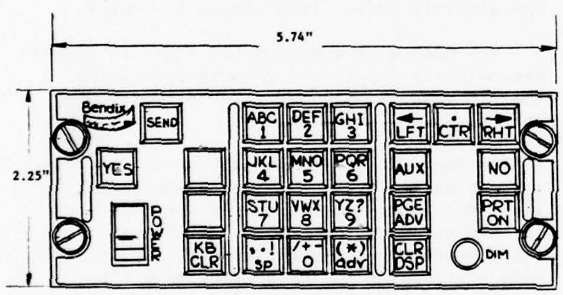

FIGURE 4
AVIONICS CONTROL PANEL

The checklist unit shown in Figure 5 is an off-the-shelf device which stores 16 pages (12 lines x 21 characters) of text in non-volatile electrically alterable read only memory (EAROM). The contents of the EAROM can be reprogrammed using a modified HP-67 calculator. The avionics will use the checklist unit to store menus of the available downlink message formats. For example, the first checklist unit page (page 0) will be an index of services which might indicate that page number 4 contained a winds aloft request message. When the pilot wants a winds aloft report he will switch the display to page 4 of the checklist unit memory. The page 4 display will indicate the information the pilot must input, via the keyboard, to request winds aloft information from the DABS ground facility. Figure 3 illustrates how the winds aloft page will be displayed. As the pilot inputs the required Location ID, Altitude, and Time, his inputs will appear adjacent to the appropriate listing. When the downlink message is ready to be transmitted the pilot will press the "Send" key. The downlink display will continue to appear on the CRT, unless the pilot clears the display or switches to a different page of the checklist unit memory. When the DABS ground facility receives the downlink message an acknowledgment of receipt will be sent to the aircraft. The color of the downlink message display will change to indicate to the pilot that the downlink message has been received (a call progress indicator). When the Applications Processor has obtained the requested information, an uplink message will be sent to the aircraft. This message will be displayed in the center 4 lines of the display.

The airborne terminal currently being procured represents only one possible implementation out of the many possible. The FAA will implement both more complex and less complex airborne terminals for future tests. As previously stated, the development of standard avionics is not an objective of this program. We believe this is best left to the avionics industry and their wide range of customers, the air carrier and general aviation users of the airspace. The program will, however, define the services available, how they are to be used and how the information is sent over the link. The standard which will result will be the basis for the development by industry of the necessary spectrum of avionics.

SUMMARY

The development of ATC applications for the DABS data link which can be implemented by the mid 1980's is proceeding. Experimental work to be conducted this winter will lead to formal test and evaluation of a first package of data link services late in 1979. The automation capabilities built into other FAA R&D programs are being used as the sources and destinations of many data link messages but new data link services are also being studied.

Several versions of possible avionics equipment are being developed to support the development and testing of the candidate services. However, it is felt that operational avionics of many kinds will eventually be developed by industry once the services are fully defined and the appropriate National Standard is issued.

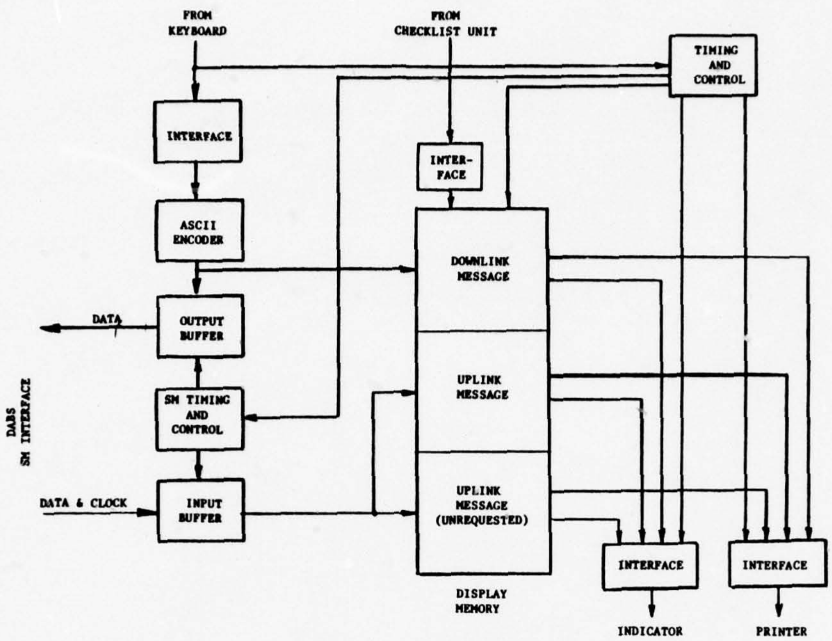

FIGURE 5

AVIONICS INTERFACE UNIT

ACKNOWLEDGMENT

The author wishes to acknowledge the contributions of the many people who supported and contributed to the definition of this program and who are dedicated to its successful conduct. Personnel from FAA's Air Traffic and Flight Standards Services assisted in defining the candidate services. The experimental program at the DABSEF was developed with the full support of a number of Lincoln Laboratory, DOT/TSC, NAFEC and SRDS personnel. Finally the contributions of ARD-230 branch personnel; Raymond Hilton, Manuel Gonzalez, and Ronnie Jones are acknowledged for their many contributions to the development of the program.

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DISCRETE ADDRESS BEACON SYSTEM

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BIOGRAPHY

P. Douglas Hodgkins received his B.S. degree in Mechanical Engineering from the University of Maine in 1959. He served as Technical Advisor to the Navy AIMS and Landing System Project Office. He joined the FAA's Systems Research and Development Service in 1974 and served as a Branch Chief in the Microwave Landing System Division. Mr. Hodgkins has extensive major system development experience and was selected to head the DABS development program for the Communications Division.

ABSTRACT

This paper describes the signal waveforms and computer architecture used in the Discrete Address Beacon System (DABS). The Discrete Address Beacon System represents a major systems development aimed at providing upgraded ATCRBS surveillance with sufficient aircraft capacity to meet air traffic growth well into the next century. It will also provide improved automation services and ground based Automatic Traffic Advisory and Resolution Service (ATARS) through its integral high capacity digital data link. The total compatibility of DABS with ATCRBS through the use of compatible signal waveforms has been demonstrated during feasibility testing. Three engineering models are being manufactured employing unique high reliability and data integrity distributed computer architecture for further test and evaluation in a high density air traffic environment. Initial results indicate the use of distributed processing for this application will be highly successful. The Technical Data Package resulting from this effort, in April 1980, will be used to procure production DABS for implementation in the National Airspace System possibly commencing as early as 1984.

BACKGROUND

The need for improvement in the Air Traffic Control Radar Beacon System (ATCRBS) was recognized early in 1969 by the Air Traffic Control Advisory Committee (ATCAC).[1] This committee was formed by the Department of Transportation (DOT) to examine the needs of the air traffic control system in the 1980's and beyond, and make recommendations for systems development. The ATCAC report recommended improvements in several areas which later became elements of the Upgraded Third Generation Air Traffic Control System. Among the several recommendations were two related to aircraft surveillance that were later combined to become the Discrete Address Beacon System. These were the recommendations to upgrade the ATCRBS by adding discrete Addressing capability and to develop a ground based automatic separation assurance capability known as Intermittent Positive Control (IPC), later renamed Automatic Traffic Advisory and Resolution Service.

The specific surveillance needs identified by ATCAC were with regard to increasing the capacity of the beacon system to meet future air traffic growth, particularly in general aviation; increasing automation through data link communications to improve productivity; and improving performance of the beacon system in general. Improving ATCRBS was oriented toward eliminating problems such as synchronous garbling of beacon replies in a high aircraft density environment such as Los Angeles, reflecting false targets and code garbling.[1] Synchronous garble occurs when two or more aircraft are at the same range and azimuth, but at different altitudes. The replies arriving at the ground station overlap one another causing cancellation or code garbling. Tabulations of the most severe ATCRBS problems reported in 1977 for terminal and en route ATC facilities are shonw in Figures 1 and 2.[2]

MOST SEVERE ATCRBS PROBLEMS, ARTS III FACILITIES REPORTING, 1977

SITES	SYMPTOM	CAUSE
54%	REFLECTION FALSE TARGETS	POOR RADIATION PATTERN; INEFFECTIVE SLS
49%	ERRONEOUS/MISSING MODE C REPORTS	INEFFICIENT REPLY PROCESSING/ SYNCHRONOUS GARBLE
41%	SIDE LOBE FALSE TARGETS	INEFFECTIVE SLS; POOR RADIATION PATTERN
36%	LOST TARGETS DUE TO HOLES IN COVERAGE PATTERN	POOR RADIATION PATTERN + IMPERFECT SITING
26%	AZIMUTH SPLITS	OVER-INTERROGATION + IMPROPER REPLY PROCESSING
16%	DOUBLE TARGETS (DOWN-LINK MULTIPATH)	HOSTILE TERRAIN + POOR ANTENNA

FIGURE 1. MOST SEVERE ATCRBS PROBLEMS ARTS III FACILITIES REPORTING, 1977

MOST SEVERE ATCRBS PROBLEMS. EN ROUTE FACILITIES REPORTING, 1977

SITES	SYMPTOM	CAUSE
[illegible]	SIDELOBE/SPILLOVER FALSE TARGETS	LOW NAFIF DIRECTIVITY + POOR SLS
54%	REFLECTION FALSE TARGETS	INEFFECTIVE SLS + HOSTILE TERRAIN
40%	LOST TARGETS DUE TO REDUCED LOW-ANGLE COVERAGE	IMPROPER NADIF TILT ADJUSTMENT
39%	AZIMUTH SPLITS	OVER-INTERROGATION + POOR REPLY PROCESSING
35%	RANGE SPLITS	IMPROPER REPLY PROCESSING
35%	PHANTOM TARGETS & GARBLED CODE DATA	IMPROPER REPLY PROCESSING
23%	ERRONEOUS/MISSING MODE C REPORTS	INEFFICIENT REPLY PROCESSING
17%	SYNCHRONOUS FRUIT/SECOND-TIME-AROUND FALSE TARGETS	NON-STAGGERED INTERROGATION PRF

FIGURE 2. MOST SEVERE ATCRBS PROBLEMS EN ROUTE FACILITIES REPORTING, 1977.

PRODUCTS AND EXPECTED RESULTS

Completion of the DABS program will result in technical performance specifications (Technical Data Package) suitable for production DABS sensors for implementation in the National Airspace System. Two Technical Data Packages (TDP) are scheduled, one for single site implementation in April 1980 and the second for adding DABS sensor-to-sensor communications (network operations) required for improved surveillance, sensor-to-sensor aircraft handoff and ATARS.

Key program milestones and schedules leading to the TDP's are shown in Figure 3.

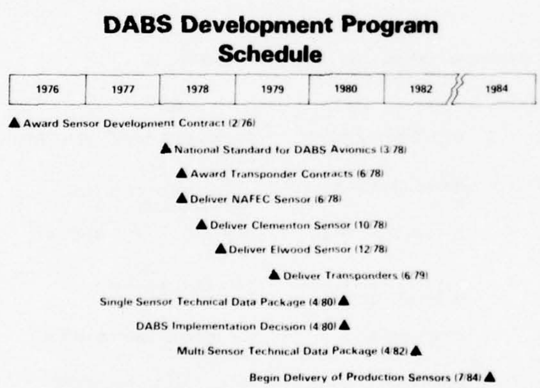

FIGURE 3. DABS DEVELOPMENT PROGRAM SCHEDULE.

It is expected that introduction of DABS in combination with a new beacon antenna system currently in production for terminal application will overcome all known difficulties with ATCRBS while providing increased surveillance capacity for the year 2000 and beyond, as well as providing a high capacity data link for automated separation assurance (ATARS and BCAS) and other ATC automation services.*

TECHNICAL APPROACH

The approach taken in formulating the DABS concept design was to undertake a concept feasibility program at Massachusetts Institute of Technology's Lincoln Laboratory. The objective of this initial phase (Phase I) was to find frequencies and waveforms that were completely compatible with the internationally and nationally standardized Secondary Surveillance Radar (SSR) and ATCRBS, respectively. To provide a high degree of hardware commonality between ATCRBS and DABS both in the aircraft and on the ground, it was decided to investigate the possibility of sharing the two ATCRBS frequencies (1030 MHz for interrogations and 1090 MHz for replies) between ATCRBS and DABS. This approach required finding a way to reduce the ATCRBS Pulse Repetition Frequency (PRF) sufficiently to allow time for the processing of DABS replies. The upper limit for the ATCRBS PRF today, established to limit interference, is 450 per second and many interrogator sites currently operate very close to this limit. The use of monopulse direction finding was the method chosen for reducing the PRF, i.e., using sum and difference antenna patterns and the ratio of energy in each pattern to precisely locate the aircraft in aximuth to less than 0.1 degree on as few as four replies from an ATCRBS transponder, and one for a DABS transponder. Typically, the current ATCRBS, using conventional beam splitting techniques, requires up to 15 replies from each aircraft and is up to six times less accurate than monopulse.[4]

Although using monopulse for DABS was a radical departure from the traditional ATCRBS technique, the benefits were overwhelming in terms of improved accuracy combined with the three times lower PRF. The lower PRF had the additional benefit of improving the ATCRBS transponder suppression and self-generated interference or "fruit" environment reducing both by a factor of three as well.[5]

As for a compatible DABS/ATCRBS signal-in-space waveform, this was achieved simply by adding a fourth pulse (P_4), 1.5 usec after the standard P_1 - P_3 combination presently used in ATCRBS, as shown in Figure 4.

This particular waveform with the P_4 pulse is defined as the DABS/ATCRBS All-Call interrogation and is used to interrogate all ATCRBS-equipped aircraft, and for initial acquisition of the addresses of all DABS-equipped aircraft for storage in a roll-call file. The ATCRBS transponders recognize the first three conventional pulses; P_1, P_2 and -P_3, but ignore the P_4 pulse, whereas DABS transponders recognize

*Applications of the DABS data link for ATC is the subject of a separate technical paper published in these proceedings.

the presence of the P 4 pulse as a request for its discrete address. If there is no P 4 pulse present, as there wouldn't be from an ATCRBS ground station interrogation, the DABS transponder will reply in the conventional ATCRBS mode and format. Once the DABS ground sensor has acquired a DABS aircraft on roll-call, the transponder is locked out from future all-calls, except under well-defined operational rules, and replies only when specifically addressed with its unique *24-bit discrete* address code.

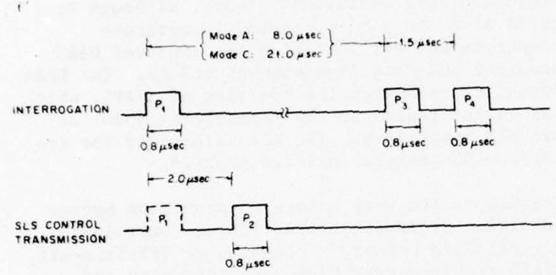

FIGURE 4. ATCRBS/DABS ALL-CALL INTERROGATION SIGNAL FORMAT.

The DABS discrete interrogation, as differentiated from the all-call interrogation, is accomplished by again taking advantage of the ATCRBS waveform for *compatibility*. If an ATCRBS transponder receives a P_2 pulse 2 usec after receiving the first pulse at the same relative amplitude or within 9 dB, it automatically suppresses and will not reply. With ATCRBS, the P_2 pulse is intentionally radiated everywhere but in the main antenna beam, 2 usec after P_1 to suppress ATCRBS transponders from replying to ground antenna side lobe emissions. The DABS uses this suppression scheme to cause ATCRBS transponders to suppress while interrogating DABS. This is accomplished for DABS by radiating P_1 and P_2 in the main beam at the same amplitude as shown in Figure 5.

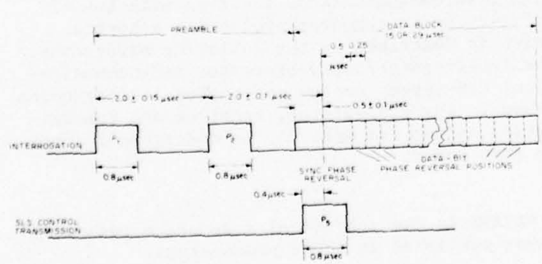

FIGURE 5. DABS INTERROGATION SIGNAL FORMAT.

DABS transponders recognize the $P_1 - P_2$ combination as a DABS *discrete interrogation* and then waits 2 usecs for the data block that follows. The data block contains either a 56-bit surveillance-only interrogation asking for the aircraft's altitude, or a combination of a surveillance message and a 56-bit general data link message, a total of 112 bits. *There is* also a third format that replaces both the 56-bit surveillance and 56-bit data frame with an 80-bit data message only. This latter format is used when long transmissions of data are required and is defined as the Extended Length Message (ELM). Up to 16 ELM segments can be transmitted sequentially to any suitably equipped DABS aircraft while it is in the main beam, requiring only a single reply to acknowledge receipt. This allows large quantities of data to be transferred without causing excessive DABS replies. Each of the shorter 56 or the 112 bit formats cause replies to be generated at the end of each message. The modulation used for the uplink data block is Differential Phase Shift Keying (DPSK), i.e., no phase shift represents zero; phase shift represents a binary one.

DPSK was chosen for the uplink over Pulse Amplitude Modulation (PAM) because it showed a clear advantage in Signal to Noise Ratio (SNR) and Signal to Interference Ratio (SIR).[6]

The DABS reply format shown in Figure 6 uses a pair of double pulses as a preamble to the data block containing either the 56-bit *surveillance* only reply, or the combination 112-bit surveillance and data message reply. The modulation used on the downlink is Pulse Position Modulation (PPM) where the position of the pulse determines whether it is a binary one or zero. PPM was selected for the downlink because it provided the best garble sensing, i.e., provides a number of pulses required for monopulse data editing.[6]

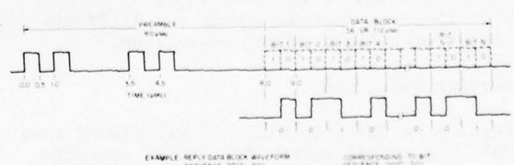

FIGURE 6. DABS REPLY SIGNAL FORMAT.

When interrogated by an ATCRBS ground sensor, the DABS transponder will reply in the standard ATCRBS format. The bit rate for all uplink formats is 4 megabits per second and 1 megabit per second for the downlink.

The high uplink bit rate was required to transmit the longest DABS message (112 bits) to the aircraft during the ATCRBS suppression interval. The ATCRBS suppression interval is 35 $\pm$ 10 usec.[3]

For the downlink, the bit rate was established at 1 MHz to basically accommodate present ATCRBS type transmitter capabilities.*

The aircraft's address is contained in the last 24 bits of each frame in both the uplink and downlink message and is overlaid with parity. The parity error protection is generated in accordance with a polynomial of the form

$$G(x) = \sum_{i=0}^{24} g_i x^i \text{ where } g_i = \begin{cases} 1 \text{ for } i = 0,3,10, \\ \text{and 12 through 24} \\ 0 \text{ otherwise} \end{cases}$$

The parity is summed modulo-2 with the 24-bit address to save overhead.

The combination of unique aircraft address codes, roll-call scheduling, and multiplicity of message formats allows considerable flexibility in manipulating the interrogations such that self-generated interference (synchronous garbling of replies) can be virtually eliminated. Of even more importance perhaps, since DABS will co-exist with ATCRBS for many years, is the fact that ATCRBS suppressions and fruit will also be reduced as previously stated, thus improving the overall performance of ATCRBS.

All of the other ATCRBS difficulties noted in Figures 1 and 2 are overcome by the use of monopulse and a new high performance antenna system currently in production.

DABS Concept Tested

The compatibility of the DABS/ATCRBS interrogations and reply formats just described was fully demonstrated during the feasibility phase. This was accomplished by constructing a laboratory model sensor at Lincoln Laboratory and conducting flight tests with industry-built feasibility model DABS transponders. Over 400 flights were flown in the Boston area without any difficulties noted with local ATCRBS operations.[7]

Engineering Development

The results of the feasibility tests proved that the DABS conceptual design for ATCRBS compatibility was suitable for proceeding into an engineering evaluation (Phase II), wherein the DABS sensors would be interfaced with both en route and terminal Air Traffic Control facilities. Engineering specifications were then prepared and proposals solicited from industry for three engineering model sensors for installation and evaluation at the National Aviation Facilities and Experimental Center, Atlantic City, N. J.; the second just outside the Philadelphia, Pennsylvania terminal in Clementon, N. J., and the third at the long range radar site in Elwood, N. J.

Coincident with the DABS sensor design and feasibility testing, a new automated separation assurance capability, Automatic Traffic Advisory and Resolution Service (ATARS), was being developed. The ATARS capability was included as a resident function in the DABS computers because of processing efficiency, although it could of course, be processed in separate computers and still utilize the improved DABS accuracy and data link communications. The DABS design accommodates the addition of ATARS, which was flight tested in the feasibility model at Lincoln Laboratory. The specifications for the three DABS sensors included ATARS.*

Because of its very nature of providing backup collision avoidance protection to controlled aircraft and primary protection to VFR aircraft, ATARS requires very high data integrity and system reliability. These requirements were given primary emphasis in the contractor selection for DABS.

Texas Instruments, Incorporated was competitively selected as the System Development Contractor (SDC) because of their technical approach to solving this problem. The SDC developed a redundant distributed processing minicomputer architecture to meet the DABS reliability and data integrity requirements via a unique combination of hardware redundancy and error detection/correction features. Such features are complemented by a distributed processing architecture that is modular in nature yet simple in control design. The computer subsystem responds to all single component hardware failures in such a manner that logical and data integrity of the system is maintained.

The DABS sensor consists of three (3) main subsystems; an interrogator processor subsystem which performs the interrogation reply processing functions, and communication subsystem that transfers the surveillance data and performs the data link communications function with the ATC facility and a computer processing subsystem which is described in the following paragraphs. The interrogator/reply processor and communications subsystems employ conventional electronics found in any transmitter, receiver and communication system and will not be described further in this paper.

*There are a number of other important factors considered in the selection of both up and downlink bit rates which are described in detail in reference 6.

*ATARS is the subject of a separate technical paper published in these proceedings.

Computer Processing Subsystem

DABS computers are grouped into ensembles with four computers in each ensemble (see figure 7, block A). The computers are connected to a data bus through which they communicate to the remainder of the system. The data buses are connected to other data buses via coupler pairs. Each DABS computer consists of two central processors (CP), voting logic for the CPs and 8K of local error correcting code (ECC) memory (see figure 7, block C).

The code of a DABS computer is executed simultaneously by each CP, i.e., each clock cycle each CP executes identical code. CP execution results are compared, and if the results agree, they are passed on to local or global memory space; otherwise, the DABS computer is immediately switched off-line to prevent any erroneous data from being passed on to memory. This error causes a "bad computer" interrupt to be propagated throughout the system. The hardware failure recovery computer responds by reassigning the tasks of the failed computer to the primary standby computer. The primary standby computer downloads its assigned tasks from global memory program store. Other computer failures, e.g., an uncorrectable local memory error will cause the same interrupt to be generated with a standby computer again assuming the responsibilities of the failed computer.

The hardware failure recovery computer is "monitored" by the primary standby computer in the event that the recovery computer should fail.

DABS computers communicate with other DABS computers and external interface devices via the global memory address space. Each global memory module is provided with error correcting code such that all single bit errors are corrected and all double bit errors are detected. Global memory modules are configured in pairs (see figure 7, block D). In each pair, one module is designated the primary memory module, the other, the secondary. Both memory modules occupy the same address range. When a DABS computer writes to the module pair, the data are written into both the primary and secondary module assuring that a backup copy of the data is always available. Data are "fetched" only from the primary memory module. If a primary memory module fails, an interrupt is generated and the hardware failure recovery computer responds by adjusting the status parameters of the memory module such that the primary is taken off line, and the secondary memory module will be declared "primary" so that subsequent read and write commands will result in data being transferred only to/from the new primary module.

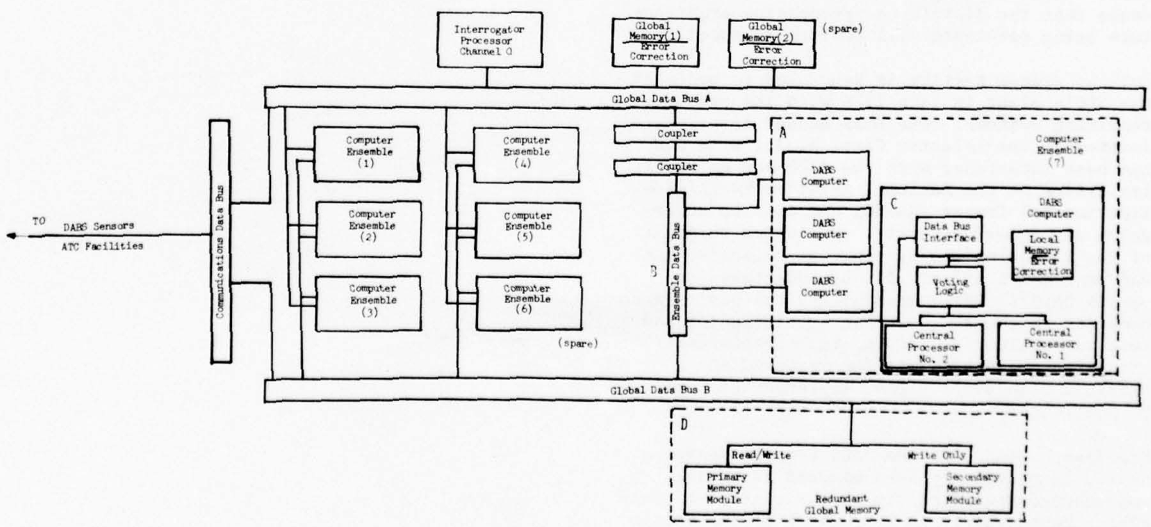

FIGURE 7. COMPUTER SUBSYSTEM ARCHITECTURE.

The global memory modules are partitioned between two major global data buses. This partitioning permits a more even distribution of data bus communications traffic and thus reduces the "wait time" overhead associated with bus availability.

SUMMARY

After several years of intensive analysis and feasibility studies, including assembly of a laboratory sensor and flight testing the DABS concept, it was concluded that the characteristics of the DABS signal waveforms described herein are totally compatible with existing ATCRBS.

Follow on engineering model sensors developed by industry using unique computer architecture to achieve high reliability and data integrity have been built and are currently undergoing tests.

To date, 20 DABS computers operating simultaneously have acquired, tracked, recorded, displayed and disseminated surveillance data successfully with an instantaneous load of 367 aircraft in 360 degrees with 330 of these peaked within a 130 degree sector. The DABS surveillance processing and Channel Management (interrogation scheduler and RF channel control) performed well during these tests. In addition, failures were induced in a DABS computer and in a global memory module. A DABS standby computer detected the failed computer, downloaded the proper tasks from global memory program store and returned the system to a full capacity operating state in less than 1 scan. A DABS computer detected the failure of the primary global memory module and correctly set the global memory status register thereby switching the secondary module to the "primary" state. Operational capacity was restored within 1/2 scan. These tests give a high degree of confidence that the distributed processing architecture being developed will perform as specified.

Full up system testing is scheduled to begin at the SDC's plant in late 1978 with the two remaining systems. One DABS sensor is presently located in the Atlantic City, N. J., area and has been interfaced with the ARTS and en route facilities at the National Aviation Facilities Experimental Center (NAFEC) and will be undergoing ATC interface tests. Following shipment of the remaining two systems, an extensive test and evaluation effort will be undertaken to verify DABS/ATCRBS compatibility and performance benefits to the ATC. At the conclusion of the test and evaluation effort, technical specifications for production will be prepared and a National Standard for DABS implementation will be published.

Mr. Joseph DeMeo, of the DABS Program Managers Staff, is gratefully acknowledged as having contributed significantly to the content of this paper, particularly as it relates to the design of the DABS computer architecture.

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MOVING TARGET DETECTION

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BIOGRAPHY

Donald H. Turnbull is the MTD Project Manager in the Communications Division of the Systems Research and Development Service. He received his B.S. in electrical engineering in 1968 from Duke University. He has taken graduate courses in administration at Southern Methodist University, George Washington University and George Mason University. Prior to joining the FAA in 1970 he worked for 2 years for LTV Aerospace Corporation, Special Support Equipment Division in Dallas.

ABSTRACT

This paper describes the development of the Moving Target Detection (MTD), on improved radar clutter processor. The MTD development program was established by the FAA to overcome the limitations experienced by existing Air Traffic Control radars in detecting small aircraft in the presence of clutter. The types of clutter experienced by these radars are ground clutter, precipitation clutter, angel clutter (primarily birds), ground traffic, and interference. The MTD utilizes doppler filtering techniques to overcome these clutter problems.

A breadboard MTD-1 was designed and fabricated by Lincoln Laboratory under the direction of the FAA. This system was interfaced with an ARTS-III system and evaluated at the National Aviation Facilities Experimental Center. The results of the evaluation were favorable and a decision was made to develop two MTD-II field evaluation model systems which will be used for operational field tests at a selected terminal radar and an en route radar site. These tests will commence in the summer of 1978.

BACKGROUND

Introduction

The MTD is an advanced radar signal processor developed by Lincoln Laboratory under ths sponsorship and direction of the Systems Research and Development Service of the Federal Aviation Administration. The objective of the effort was to develop a processor that would overcome the problems that existing Air Traffic Control (ATC) radars experience in clutter environments; namely, poor detection of small aircraft and excessive false alarms. These problem areas are discussed in more detail below. The MTD development effort has gone through three major phases. These are:
1) analysis of ATC radar problems and formulation of techniques for solving these problems;
2) design, fabrication and test of a breadboard MTD-1 at the National Aviation Facilities Experimental Center (NAFEC) to prove the MTD concept; and 3) design, fabrication, and test of field evaluation model MTD-II's for both en route and terminal radars. The MTD-II systems will undergo operational evaluation at selected field sites. At the present time, the field evaluation model MTD-II systems are in final checkout.

Problems With Existing Radars

As stated above, the FAA's existing ATC radars encounter difficulties in detecting small aircraft and experience excessive false alarms in clutter environments. The various types of clutter and their affect on the radars are discussed below.

Ground Clutter. At a typical FAA ATC radar site, ground clutter will extend out about 20 miles, although it can extend out considerably further in range in hilly or mountainous terrain. This clutter varies considerably from point to point because of the discontinuous nature of the reflectors (mountains, buildings, power lines, water towers, etc.) and the shielding effects of these reflectors. While ground clutter may look continuous on a display, in reality there are many "holes" in the clutter because of shielding.

Three basic techniques presently are used by FAA radars to reduce the effects of ground clutter. These techniques are: Moving Target Indicator (MTI), antenna tilt, and shielding. The MTI system utilized by the Airport Surveillance Radars (ASR's) employs a three pulse canceller with IF limiting. The purpose of the limiting is to perform a constant false alarm rate (CFAR) function so that the clutter residue is reduced to the average noise level and therefore is not displayed on the controller's scope. The disadvantage of limiting is that the clutter spectrum is spread out and the potential subclutter visibility (SCV) is reduced. Calculations have been made that indicate that an ASR-7 radar at 15 nautical miles using a clutter level from mountainous terrain that is exceeded only 5 per cent of the time requires an improvement factor of 46 dB to detect a 1 m^2 target (typical small aircraft). Since the ASR radars have an improvement factor of approximately 25 dB it can be seen that there are many times when it is not possible to detect small aircraft flying over ground clutter. The wide nothc around zero velocity and the first blind speed due to MTI also

creates detection problems. The blind speed problem can be eliminated through the use of staggered pulse repetition frequency (PRF), however, the notch around zero velocity means that aircraft will not be detected for a considerable number of scans when they are flying tangential to the radar. In an effort to reduce the area subjected to the tangential blind speed problem, the most modern FAA radars (ASR-8 and ARSR-3) utilize range-azimuth gating which essentially maps out the areas in which ground clutter is present and gates on the MTI only in those regions, thereby permitting normal (non-MTI) radar coverage in the areas in which no ground clutter is present.

Greater signal-to-clutter ratios can be obtained by tilting the antenna up, however, this sacrifices the low altitude coverage at longer ranges. The most modern FAA terminal (ASR-8) and en route (ARSR-3) radar systems utilize this technique to reduce close-in ground clutter by having dual beam antennas. At short ranges the upper beam is used to reduce ground clutter while the lower beam is used at longer ranges to maintain low angle coverage.

The third way existing FAA radars reduce the effects of ground clutter is through shielding. The selection of a radar site and determination of antenna height involves a trade-off between two conflicting requirements. Maximization of low altitude long range coverage would dictate a site with few close-in obstructions and a high antenna height. Minimization of ground clutter dictates a low antenna height and the presence of close-in obstructions to shield out sources of ground clutter. In siting a radar, the FAA must select the best compromise between these conflicting requirements.

Second-time-around ground clutter occurs during conditions of anomalous propagation when the radar waves are bent back to earth and are reflected from points beyond the normal range of the radar. In this situation, ground clutter returns from the next-to-last pulse are mixed in with radar returns from the last pulse. In FAA radars utilizing a magnetron transmitter (ASR-4, 5, 6, 7, and ARSR-1, 2) a fixed phase relationship is not maintained between pulses and therefore there is no way to filter out second-time-around ground clutter. In radars with coherent transmitters (klystron) the second-time-around clutter will be cancelled out by the MTI if a constant PRF is used. However, with staggered PRF the range of the second-time-around clutter will vary from pulse to pulse and therefore the clutter cannot be cancelled.

Precipitation Clutter. Returns from precipitation inhibit the detection of aircraft by saturating the controller's display and masking aircraft returns. This problem occurs on both terminal and en route radar systems; however, it is more severe on the terminal systems because precipitation backscatter on S-band systems (terminal radar frequency) is approximately 15 dB higher than that on L-band systems (en route radar frequency). The spectral spread of the precipitation depends upon the prevailing wind and the wind gradients within the precipitation area. The MTI circuitry will eliminate only the zero radial velocity components of the precipitation in the MTI regions.

FAA radars utilize circular polarization and Log-FTC-antilog circuitry to reduce the effects of precipitation clutter. Circular polarization improves signal to clutter ratio by reducing the precipitation backscatter about 16 dB while reducing aircraft returns by only about 2-6 dB. Log-FTC-antilog circuitry provides a CFAR function by automatically lowering the radar receiver gain at each range by approximately the amplitude of the precipitation return. This prevents precipitation clutter from saturating the radar display and permits detection of aircraft targets whose return is stronger than that from precipitation.

Although it is desirable to remove the precipitation from the controller's display to allow better aircraft detection, there is a conflicting requirement to present weather information to the controllers that will permit the separation of aircraft from potentially hazardous storms. Existing FAA radars can present only precipitation reflectivity and even that presentation is not properly calibrated for STC attenuation, MTI velocity response, antenna beam shape, and the use of circular polarization. Further, reflectivity has only an indirect relationship to areas of turbulence, in that severe turbulence may exist in areas of a thunderstorm other than the high precipitation reflectivity cores.

In order to be completely safe in separating aircraft from hazardous turbulence an accurate indication of areas of turbulence must be obtained. At the present time, the most promising means of achieving this appears to be through the use of doppler measurements to obtain the needed information. Since the MTD uses doppler filtering for clutter rejection, the FAA is experimenting with using MTD techniques to detect hazardous turbulence. There are also experiments being conducted to determine if MTD doppler techniques can be used to detect hazardous wind shear in the vicinity of an airport.

Angel Clutter. Angel clutter is a term used to describe radar returns which cannot be attributed to ground clutter, precipitation clutter, or aircraft. Experiments have been made which indicate that most angel clutter is caused by bird flocks.[2] Angel clutter problems are most severe during the spring and fall bird migration seasons. Returns from single birds at S-band range in size between 10^{-4} and 10^{-2} m^2 and although the mean return from a flock of birds is about 10^{-2} m^2 peak returns of bird flocks can be as high as 10 m^2. Since the return from a small aircraft is often about 1 m^2, it can be seen that discrimination between small aircraft and angels can be very difficult.[1&3] The problem is not limited to the FAA S-band (terminal)

radars but also applies to FAA L-band (en route) systems since the radar return from large birds is resonant near L-band.

Ground Traffic. Many FAA radar systems are sited such that they receive radar returns from ground traffic on highways and bridges. Since this traffic consists of moving vehicles, these returns are not rejected by the MTI circuitry and are displayed on the controller's scope. At the present time, the only solution to this problem is to tilt the antenna upward or to blank out the areas which contain ground traffic.

Interference. Some FAA radar systems have problems with interference from other radiating sources on or near the same frequency. As the number of radars increase, it is expected that this problem will increase especially in high radar density areas such as the Los Angeles basin. The present means for reducing this problem is to employ the video integrator circuitry in the radars.

PRODUCTS/EXPECTED RESULTS

A breadboard Moving Target Detector (MTD-I) was designed and fabricated at Lincoln Laboratory and delivered to NAFEC. The MTD-I was interfaced with an Automated Radar Terminal System (ARTS-III) and given an extensive evaluation including a direct comparison with the most advanced radar video digitizer (RVD-4) developed by the FAA to that time. The MTD-I greatly improved small aircraft detection capability in all types of clutter environments. The ground clutter environment at NAFEC is shown in figure 1 with 5 mile range rings. The heaviest ground clutter is located about 7.5 miles southeast of the radar site and has peaks of 45 dB above noise level. A controlled aircraft was flown tangentially over this area and was detected continuously (figure 2). [4]

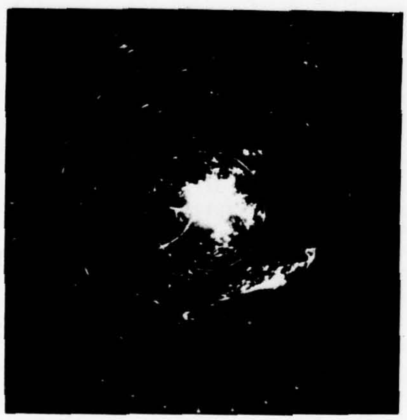

FIGURE 1. NAFEC GROUND CLUTTER.

FIGURE 2. MTD PERFORMANCE OVER GROUND CLUTTER.

Figure 3 shows the normal video presentation of rain during an MTD-I test in which the amplitude of the rain varied between 0 dB and 40 dB. A test flight was made with a small aircraft in that rain and that aircraft was continuously detected (figure 4). Tests were also made of interference and angel clutter rejection capability. Ground traffic rejection was not incorporated in the MTD-I. The results of the test and evaluation of the MTD-I at NAFEC are described in a report published in October 1977.[5]

FIGURE 3. PRECIPITATION CLUTTER.

FIGURE 4. MTD PERFORMANCE IN PRECIPITATION CLUTTER.

Based on the results of the MTD-I evaluation the FAA made a decision to develop and fabricate two advanced MTD-II systems for operational field evaluation at a terminal and en route FAA radar site. The terminal site selected was Burlington, Vermont. Burlington is a non-automated ASR-7 site located in mountainous terrain. It is also expected that there will be considerable precipitation and angel clutter at Burlington. The en route site selected is Bedford, Virginia. Bedford has an FPS-67 radar system which is remoted to the Leesburg, Virginia, Air Route Traffic Control Center. This radar is located on the top of a mountain. The Air Force partially funded the en route MTD-II program and is participating fully in the program.

Both the terminal and en route MTD-II operational field evaluations will commence during the summer of 1978 and will last approximately 6 months. During that time, both a technical evaluation and an operational evaluation using FAA controllers will be performed on the MTD-II. At the conclusion of the evaluations a technical data package will be prepared which will be used by the FAA and possibly the Air Force in writing a specification for procurement of production Moving Target Detectors.

TECHNICAL APPROACH

MTD General Description

To accomplish the required clutter rejection the MTD utilizes velocity filtering and adaptive thresholding. The entire radar coverage area is divided into range-azimuth cells (1/16 mile by 3/4 degree cells for terminal, 1/8 mile by 3/4 degree cells for en route). Each azimuth cell is called a coherent processing interval (CPI) and contains eight pulses generated at a constant PRF. From these eight pulses a series of eight generalized digital doppler filters are generated with each filter having a given velocity response (for example between 35 and 50 knots) so that the total response from all eight filters spans the spectrum between zero velocity and the first blind speed. The same filters repeat themselves for higher velocities. Each range-azimuth-doppler cell is individually thresholded for clutter rejection.

Ground Clutter Thresholding. Nearly all of the ground clutter falls into the zero velocity filter with only a little spilling over into the adjacent low radial velocity filters. Because of the discontinuous nature of ground clutter, a fine grained dynamic ground clutter map is maintained to determine the level of clutter in each range-azimuth cell. The clutter map is built up and maintained in a recursive manner by adding 1/8 of the output of the zero velocity filter on each scan to 7/8 of the value stored in the map. In this way, the clutter map can adjust itself to changes in the clutter occurring in the zero velocity filter due to weather moving in or propagation changes. The value stored in the map is used to set the threshold in the zero velocity filter and to a much lesser extent the thresholds in the adjacent low radial velocity filters.

Aircraft which have velocities other than zero do not compete with the ground clutter in the zero filter and are therefore detected. Those aircraft with zero velocity would not have been in a range-azimuth cell long enough to build up the clutter map and therefore would be detected if they are stronger than the threshold in that particular cell. This is usually the case because aircraft with zero radial velocity are broadside to the radar which is the aircraft aspect giving the largest radar return.

Blind speed problems are eliminated through the use of batch staggering. Although the PRF is constant within a CPI, it is varied in alternate CPI's. In this way, if a target is in a blind speed during one CPI it will not be in that blind speed during the next CPI. Keeping a constant PRF during the eight pulses within a CPI permits the cancellation of second-time-around ground clutter if the MTD is interfaced with a radar having a coherent transmitter.

Weather Clutter Mean Level Thresholding. The Spectral return from precipitation varies in width as well as in average velocity. These returns can therefore fall into any doppler filter and be spread over several filters. Unlike ground clutter, precipitation clutter does not vary greatly from cell to cell. For this reason, the threshold for each range-azimuth-cell is obtained by mean level thresholding for the non-zero filters. In this scheme the amplitude of the precipitation (or noise) is averaged over one mile in range centered on the cell of interest and this average is used to set the mean level threshold. Any aircraft sufficiently stronger than the precipitation clutter will be detected.

For aircraft whose radial velocity is greater than the first blind speed there is a greater probability of being detected. The reason for this is that with the PRF varying from CPI to CPI the return from the higher velocity target will

fall into different doppler filters on alternate CPI's. This means that if this target is competing with rain during one CPI, it will probably fall into a rain free doppler filter during the next CPI and therefore be detected.

Post Processing. Whenever a threshold is exceeded in any range-azimuth-doppler cell a primitive target is generated. A typical aircraft return may extend over two range cells, two or more CPI's, and several doppler filters. The purpose of the post processing function is to process the primitive target reports into accurate aircraft position reports and to reject false alarms including those caused by angel clutter and ground traffic. The primitive targets seeming to come from one aircraft are grouped together into a cluster (correlated) and then an interpolation function is performed on the cluster to find the best estimate of azimuth, range, and amplitude of the target.

A second level thresholding is performed to reduce angel clutter. The radar coverage is divided into sectors. If an excessive number of returns occur in a sector in any filter, a threshold is set to eliminate the weaker returns. In this way angel returns which tend to be lower velocity weaker returns are eliminated.

Ground traffic can be filtered out because the exact location of highways is known as is the usual radial velocity of the traffic. Returns from those locations with the known velocities can be rejected.

False alarms are rejected by a scan-to-scan correlator. Each return is compared against returns from previous scans to see if it corresponds to an existing aircraft track. Only tracks that have lasted for three scans are sent to the display for use by air traffic controllers.

Interference Rejection. Non-synchronous interference will appear on only one pulse of the eight pulses making up a CPI. Each CPI is examined to see if one of the eight pulses greatly exceeds the average pulse amplitude. If this is the case, the entire CPI is thrown out during that scan. In this way non-synchronous interference is completely eliminated.

MTD Design. The basic block diagram of the field evaluation model MTD-II is shown in figure 5. The various functions are interfaced into a system through an IEEE standard data bus. This interface is controlled by the bus controller. The radar controller accepts antenna position information and the master IF oscillator signal and outputs all the necessary triggers and pulses needed by the radar.

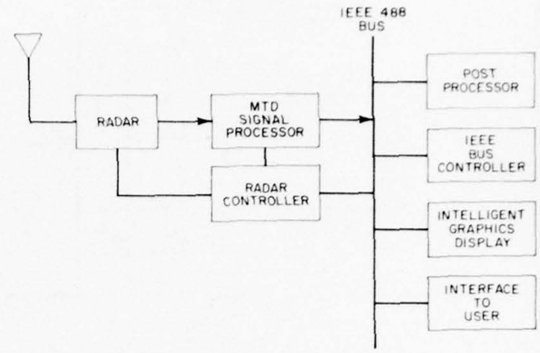

FIGURE 5. MTD-II BLOCK DIAGRAM.

The MTD-II accepts radar signals from the preamplifier which are then fed into a wide dynamic range receiver. Quadrature video detectors provide I and Q video to 10-bit A/D converters. The output of the A/D converters is fed into the parallel microprogrammed processor (PMP) which is the heart of the MTD. All of the doppler filters and the ground clutter map are generated in the PMP. The PMP is a very fast processor which can be programmed using special PMP assembly language to perform many different functions. Any required change to the MTD algorithms can be implemented through a programming change.

The parallel structure of the PMP is shown in figure 6.[6] Each processing module (PM) is identical and contains input memory, auxilliary memory, and a processing element (PE) which performs the same function at the same time in all PM's. For example in the terminal MTD-II PM #1 handles the data from 0 to 10 miles. PM #2 handles the data from 10 to 20 miles and so on. A spare PM is provided so that it can be automatically switched in to replace a failed PM. Automatic diagnostic routines will be incorporated in the PMP to detect faults and switch in the spare PM. If more than one PM fails the MTD-II will degrade gracefully by readdressing the PM's so that only the furthest range data is lost.

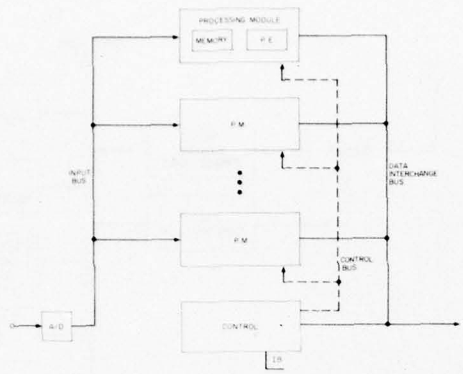

FIGURE 6. PMP BLOCK DIAGRAM.

The post processing function described previously is presently implemented in a commercial minicomputer, however before the evaluation program is completed this function will be implemented in PMP hardware. This will keep to a minimum the types of printed circuit boards required in the MTD.

For purposes of evaluation a digital maintenance display was interfaced with the IEEE bus. This display will also provide the output of the MTD.

SUMMARY

Existing FAA radar systems experience difficulty in detecting small aircraft in the presence of ground clutter, precipitation clutter, angel clutter, ground traffic, and interference. In order to overcome these difficulties, an advanced radar signal processor called the MTD was developed. The initial breadboard version of the MTD was successfully tested at NAFEC. Two second version MTD's are being developed for operational field evaluation at a terminal radar site (Burlington, Vermont) and an en route radar site (Bedford, Virginia). At the conclusion of these evaluations a technical data package will be prepared for use in writing procurement specifications for production MTD systems.

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NATIONAL AIRSPACE DATA INTERCHANGE NETWORK (NADIN) FOR AERONAUTICAL OPERATIONS

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BIOGRAPHY

Arthur K. Kingsley was born in Formoso, Kansas, and received the B.S. Degree in Electrical Engineering from Kansas State University, Manhattan, Kansas. He pursued graduate studies in Electrical Engineering at Maryland University, College Park, Maryland. He was employed by General Electric Company as a test engineer and during World War II served as a naval officer in the Bureau of Ships Magnetic Mine and Torpedo Countermeasures Laboratories. In 1947 he joined the communication equipment installation and maintenance offices of the Civil Aeronautics Agency and in 1960 the Research and Development Service of the Federal Aviation Administration. With these organizations he has performed a wide range of design, engineering and program management functions in the development and implementation of air traffic control data processing systems and communications networks and switching systems. He is currently Chief of the Data Communications Section, Communications Division, Systems Research and Development Service, Federal Aviation Administration, engaged in the computerization of network control and switching functions for air-ground and ground-ground digital communications systems.

ABSTRACT

The National Airspace Data Interchange Network (NADIN), a national ground-to-ground digital message switching network designed to replace a number of independent low speed networks and switches, is described. It integrates the present Aeronautical Fixed Telecommunications Network (AFTN), Service B system, selected Service A weather data and NAS NET into a single Aeronautical user message network. NADIN is designated to grow through planned enhancements to serve new and evolving communications requirements in support of the National Airspace System (NAS) national and international air traffic control operations and aeronautical weather services. NADIN will utilize Federal Standards for data transmission and control and computerized switching centers to achieve the goal of a fully unified data communications system. **Basic concepts and progress towards this goal are outlined.**

BACKGROUND

The FAA requirements for operational data communication services have grown steadily in recent years. Recognition and satisfaction of the requirements, however, have generally been viewed from a limited perspective. Consequently, over a long period, a variety of specialized and costly data communications services have evolved, each service intended to satisfy an isolated communication need. The FAA has thus acquired a number of separate communication networks, incorporating different standards and procedures, each with severely limited growth capability, incapable of mutual support, largely unable to communicate with each other, and expensive to operate and maintain. The discrete networks in their current configuration cannot economically be improved and upgraded to meet the communication requirements of the NAS. As the result of work performed under a study contract completed in 1972 by the Systems Research and Development Service (SRDS), it was determined that a fully integrated air traffic control ground-to-ground data network was more economical and efficient than separate interconnected systems.[1] The NADIN concept meets this criterion since it will integrate these diverse networks into a single multiuser message network through the use of state-of-the-art technology. NADIN initially will replace a number of inefficient independent, low-speed networks and switches, as indicated pictorially in Figure 1. It is planned that NADIN enhancements will be implemented in discrete, stand alone, manageable stages over a multi-year period as new system requirements for data transfer can be sufficiently defined for inclusion into the system.

PRODUCTS/EXPECTED RESULTS

The NADIN is designed to meet the operational requirements identified by the Air Traffic Service (AAT). These relate to the upgrading and modernization of the Service B system and the international AFTN with their associated switching centers at Anchorage, Honolulu, and Kansas City.[2] Additional requirements for air traffic control data transfer have been identified for the Automated Flight Service Station (FSS) program, the Central Flow Control program and the Weather Message Switching Center (WMSC). In addition to basic data transfer capabilities required for the above, the AAT has requirements for:

- Improved error checking and message integrity through use of character check bits and message check characters.

- Full (two-way) interface of all ATC system users with the NAS 9020 computer.

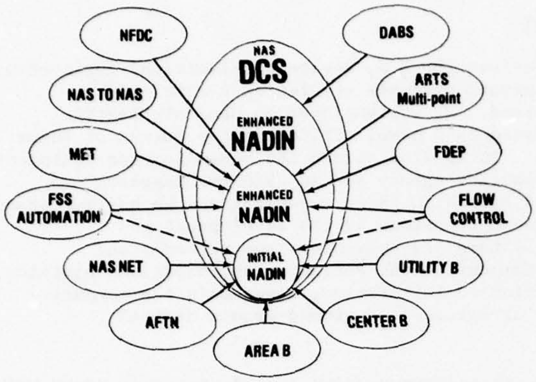

FIG. 1 PLANNED EVOLVEMENT OF INITIAL NADIN INTO THE COMMUNICATIONS SUBSYSTEM OF THE NATIONAL AIRSPACE SYSTEM.

- Improved collection of ATC statistical data from field facilities.

- System growth for the handling of aircraft movement and control data.

Other deficiencies of today's data transfer networks are:[2]

- Excessive circuit cost.
- Obsolete equipment which is difficult to maintain.
- Operation and maintenance are labor intensive (high manpower requirements).
- Incompatible formats and procedures.
- Inadequate network management.

The means by which the FAA will meet the above ATC communication requirements and overcome the deficiencies of today's data transfer networks is through the development of NADIN. Additionally, NADIN will establish uniformity of equipment and procedures and gain an ample margin of capacity and performance for current data communication requirements, with capability for growth to accommodate future needs.

Initial NADIN (i.e., NADIN I) provides a backbone network architecture to provide for the transfer of the digital data depicted in Figure 1 and be capable of expansion to meet future data requirements. The initial system specifically provides for incorporation of the present Aeronautical Fixed Telecommunications Network (AFTN), Service B system (a family of low speed teletypewriter networks used primarily to transfer flight plan information) and the NAS NET, a leased low speed polled teleprinter network linking the National Aeronautical Experimental Facility (NAFEC) to the 20 CONUS Air Route Traffic Control Centers (ARTCCs). NADIN I will also interface with the WMSC to provide selected Service A weather products to ARTCCs, interface with the NAS 9020 computers, the Flight Service Information System (FSIS), presently under development and the initial central flow control Air Traffic Control System Command Center (ATCSCC). Subsequent additions to NADIN under the NADIN enhancement program will be a further integration of weather services (Service A collection and distribution) and total FSIS requirements for data transfer as well as further integration of data communication used in support of the air traffic control mission.

SYSTEM DESCRIPTION

The NADIN architecture relies on the use of communication concentrators, one located with each ARTCC, including Anchorage, Honolulu, and San Juan (See Figure 2). The concentrators will control connected data communication terminals, which include the NAS ARTCC computers and will be interconnected through two data switches, each capable of managing the entire network under emergency and test conditions. The switching centers are to be collocated with ARTCC facilities in Salt Lake City, Utah, and Atlanta, Georgia. Communication standards employed in the NADIN design provide for efficient operation over all types of transmis sion media, including domestic and international satellite operations. The NADIN system baseline design was selected after extensive modeling of various alternatives, operational considerations and the need for a system that could be expanded and upgraded to accommodate new requirements in the most cost beneficial manner.[3]

The NADIN message switches receive all terminal transmissions and route the messages to their desitnations. Additionally, the switches perform critical data journalling functions on each message, to permit follow-up in case of lost or garbled messages, as well as to provide statistics on network performance. This centralized data collection and analysis facility provides continuous information on the demands placed on the network and the ability of the network to meet those demands; e.g., the detection of circuits and nodes approaching saturation, and the identification of facilities that are under-utilized.

Analysis have confirmed the avialability of immediate cost reductions in existing communication services through the communications consolidation allowed by initial NADIN. To users currently operating with a recognized communication link or network protocol, NADIN will be transparent, permitting immediate implementation without disruption of services and without extensive or expensive modifications to existing systems or software. The brunt of the interfacing requirement will be borne by the NADIN concentrator for these existing in-service systems. The initial NADIN design

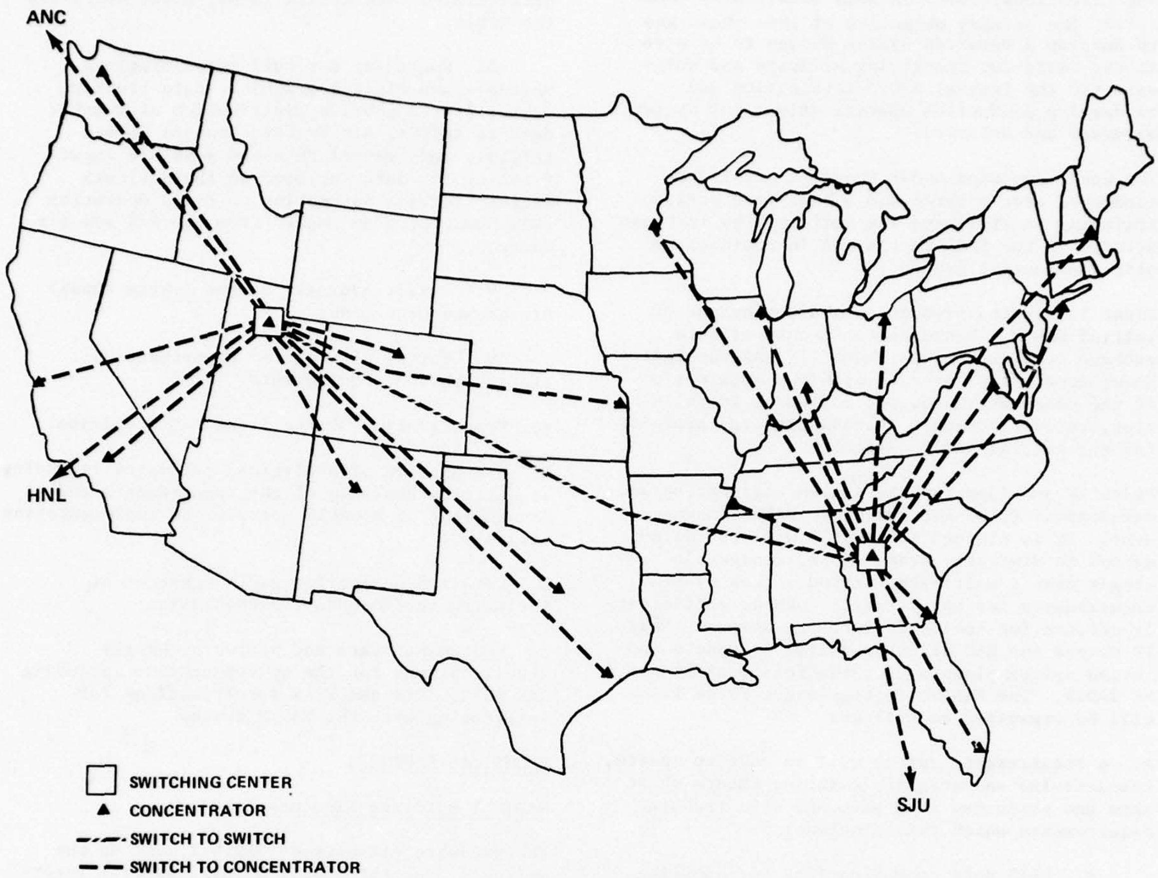

FIG. 2 NADIN BACKBONE NETWORK.

provides for a number of interface options.[4] For those planned ATC information systems whose digital communications needs are as yet undefined, NADIN will provide a list of standardized communications interfaces from which, in most cases, an appropriate selection can be made.

PROGRAM MILESTONES

In carrying out the program, the FAA is using a phased approach for the development and acquisition of the initial NADIN system and enhancements thereto. Phase I of this program has been completed. Work under Phase II is essentially complete except for ongoing engineering leading up to Phase III. (See Table 1).

Phase I provided requirement validation and development of a concept and strategy for a system modernization. The objective of this phase was to define and characterize system requirements through the 1985 time period. This was accomplished by synthesizing requirements and technology, and by conducting computer aided analysis in recommending the most viable technical development strategy for system modernization in the most cost effective manner.[1]

TABLE 1
NADIN DEVELOPMENT SCHEDULE

Phase I	Initiated	Completed
Characterization of Existing Networks and Requirements Validation	1974	1975
Phase II		
NADIN I Design and Specification	1975	1978
Phase III		
NADIN I Procurement and Deployment	1978	1981
Phase IV		
E&D Design for NADIN Enhancements	1978	1981

Phase II accomplished system design and specifications, based on data obtained in Phase I.[3,4] The primary objective of this phase was to develop a detailed system design to be used as the basis for specifying hardware and software for the initial NADIN acquisition and to develop production specifications for system hardware and software.

The work completed under Phases I and II was conducted over a three and a half year period beginning in FY-74 and was performed by in-house efforts of the SRDS in the FAA in conjunction with contractual support.

Phase III is the production and deployment of initial NADIN. Based on the technical data package completed under Phase II, FAA Washington Headquarters will proceed with the acquisition of the necessary hardware, software, installation, cutover, on-site installation and training for the initial NADIN system.

Phase IV provides for the system engineering and development (E&D) for follow-on NADIN enhancement. It is planned that NADIN will be implemented in discrete, stand alone, manageable stages over a multi-year period as new system requirements for data transfer can be sufficiently defined for inclusion into the system. Phase IV covers the E&D effort required to update and revise system planning for the follow-on stages of NADIN. The E&D activities under Phase IV will be organized as follows:

A. A requirements survey will be made to update, characterize and quantify existing future short term and projected long term AAT data transfer requirements which shall include:

1. FSIS data communications for handling data exchanges between Flight Service Data Processing Systems (FSDPS), WMSC, other ATC facilities;

2. Flow control data communications for ATCSCC exchanges with industry, ARTCCs, Automated Radar Terminal Systems (ARTS) and manual FSS locations;

3. Flight Data Entry and Printout (FDEP) communications using replacement devices operating in the medium speed range on multipoint circuits using standard communication practices;

4. ARTCC/ARTCC communications including the capability for non-NAS data exchanges such as with Canada;

5. ARTCC/ARTS communications for ARTS II, ARTS III, ARTS IIIA and EARTS with the capability for multipoint circuitry to terminal locations;

6. Interface with NFDC/IS at Oklahoma City for exchanges of airport data base information;

7. Upgrading field office terminal capability (Air Traffic Service, Airway Facilities Service, Flight Service Stations) to provide data base access (NFDC, WMSC, etc.) via the NADIN;

8. Upgrading for full meteorological messages and digital graphics, data trunking capability to provide distribution of weather data to ARTCCs, Air Traffic Control Towers (ATCTs), and manual FSSs and possible input trunking for data included in the National Weather Service Automation of Field Operation (NSW AFOS) program needed from the NWS and Air Force;

9. Direct Address. Beacon System (DABS) Air/Ground Data Link;

10. Survey of selected Department of Transportation requirements.

B. Specification of the first NADIN upgrade.

C. Preparation of analytical estimates including sensitivity analysis of the requirements and development of a NADIN upgrade and implementation strategy.

D. Detailed design for NADIN enhancement including recommended implementation.

E. System hardware and software changes specifications for the system upgrade including NAS 9020, ARTS and FSIS specifications for interfacing with the NADIN system.

TECHNICAL APPROACH

NADIN I Hardware Elements

The hardware elements of NADIN I make up the switches, concentrators, modems, special interface devices. The detailed physical features of these network components, have not been specified but are dependent upon the contractor implemtation of the functional and operational requirements for the NADIN. Nevertheless, it is possible to describe in somewhat general terms the features of these elements.

NADIN I Switches

Figure 3. The NADIN switches may be medium-scale digital computers, not different in basic features from present state-of-the-art communications oriented computers. The processing functions are weighted toward input/output rather than calculation and data manipulation. Since the system is dedicated to a specific set of functions rather than to an open-ended list of applications, the requirements for program and data file storage and retrieval are relatively modest. Thus, the switches will have relatively small secondary storage capability (disk, drum, or tape) and moderate-sized primary storage (core memory), but will have input and output channels for a substantial number of communication circuits.

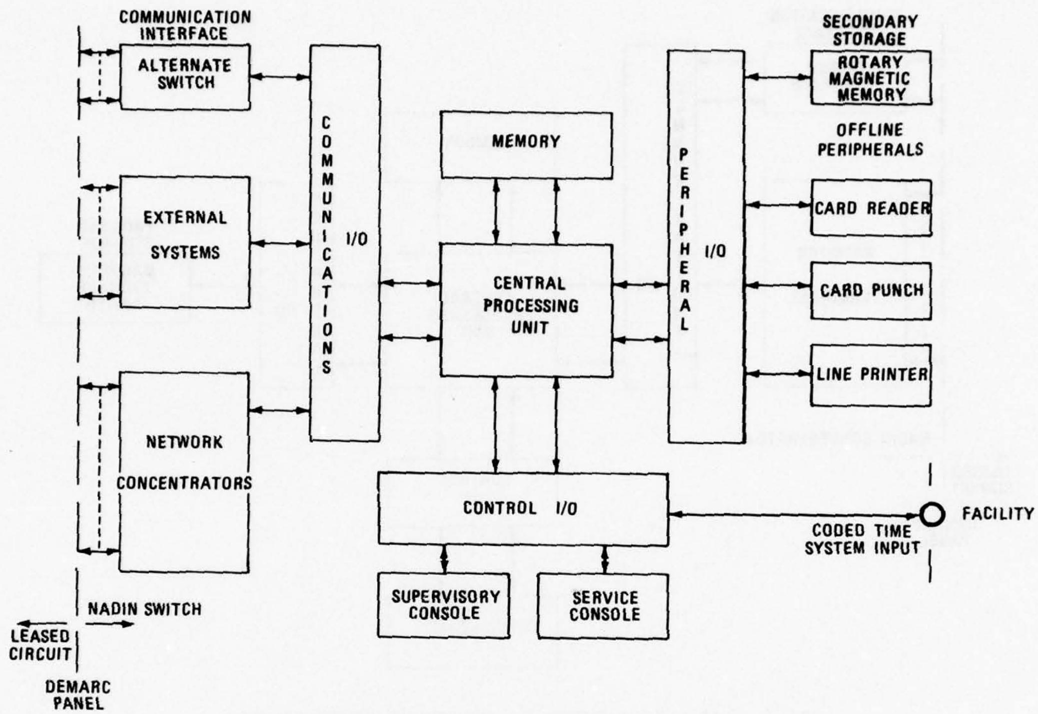

FIG. 3 NADIN SWITCH FUNCTIONAL BLOCK DIAGRAM.

A. Switch Operator Consoles. The supervisory console associated with each switch will have functions beyond the usual computer operator's requirements. Since the system is normally running a fixed set of programs, the system operation will have virtually none of the common functions except occasional tape and disk mounts and dismounts. Primary concern is with monitoring network performance and making adjustments and corrections should the automatic network actions be unable to cope with overloads, malfunctions, or other problems. One or more intercept operators will provide service on messages with routing or format problems and screen certain requests for retransmission. All these positions will have terminals providing keyboard input, cathode-ray and printed output, and access to switches controlling appropriate system functions.

B. Redundancy. In order to achieve the level of nodal availability required (99.98 percent), it is likely that some form of equipment redundancy will be used. Many options are available, the choice being made by the contractor in accordance with his design philosophy.

NADIN I Concentrators

Figure 4. The concentrator hardware is to be basically a subset of the switch equipment. There are two major differences. The concentrators, unlike the switches, will not depend on any electromechanical storage devices (disks, tapes, etc.) for their primary functioning. However, a tape cassette or similar device will be used to store the concentrator program or reload in case of malfunctions. Also, as noted earlier, the concentrators will not ordinarily operate under local control. They will be equipped with a simple control panel rather than an elaborate supervisory operating console like that associated with a switch. Remarks concerning redundancy in the switches apply equally to the concentrators.

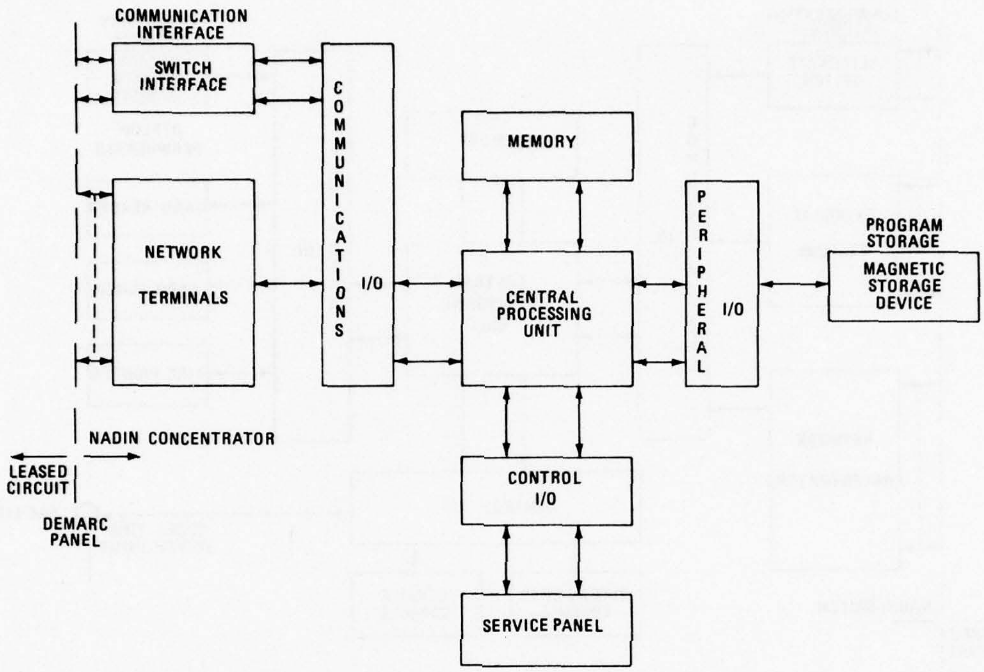

FIG. 4 NADIN-I CONCENTRATOR FUNCTIONAL BLOCK DIAGRAM.

Modems

NADIN I will use five basic types of modems to terminate the various classes of circuits in the network. There may be minor variations constituting subcategories with the basic five. The basic types are as follows:

1. 0-300 b/s, asynchronous, half and full duplex.
2. 0-1800 b/s, asynchronous, half and full duplex.
3. 2400 b/s, synchronous, half and full duplex.
4. 2400 and 4800 b/s, synchronous, half and full duplex.
5. 2400, 4800 and 9600 b/s, synchronous, full duplex.

The types (1) and (2) will be used between concentrators and low-speed terminals (many terminals in this category operate on a current-loop basis and will not require modems). Types (3) and (4) will be used between medium-speed terminals and concentrators, and the type (4) between concentrators and switches. Type (5) will be applied to switch-to-switch communications. In addition, circuits between NADIN switches and external systems will use modems of any of these types as appropriate.

CIRCUITS

NADIN I and its connected terminals will operate with dedicated circuits. Dialed connections will be used as backup when needed and possibly as a primary medium for any terminals that do not require full-period service. The NADIN full-period circuits will generally be provided by the communication common carriers.

NADIN I OPERATING PRINCIPLES

Message Flow

The basic principle of NADIN I operation is close control of message flow. Messages are accepted for processing only when facilities are available to handle them and are routed and processed

through the system to assure prompt delivery. The flow of messages within NADIN I and between NADIN I and its terminals and connecting systems is closely controlled to prevent overloads while using circuit and processing facilites as efficiently as possible considering system busy hour loading, delay and availability/ reliability requirements. These contrasting goals are to be achieved by proper management of the system software and of the storage capabilities of the switches and concentrators and those inherent in the terminals.

A. Subscriber Classification. NADIN I will be serving a variety of terminal types ranging from low speed teleprinter (Model 28 teletypewriters) medium speed terminals (DTEs) and computers (NAS 9020 and WMSC DS-714). Most low speed subscribers will be served via polled multi-point circuits from the concentrators. Most medium speed subscribers including the WMSC computer will be served over dedicated links using either message-oriented or block-oriented control procedures between the subscribers and the concentrators. Message transfers between NADIN I and the NAS 9020 computers requrie a special interface between the computer and the concentrator.[5] Messages between switches and between switches and concentrators will be transmitted on a frame-by-frame basis. [6] In general, frames of multi-frame messages, although transmitted in proper sequence, will be interspersed with frames of other messages. The node serving the destination access line will separate the frames of a given message from the other message frames that may be mingled among them and transmit them over the destination access line, either continuously, as in the low-speed case, or as individual frames in the case of access lines using message-oriented blocking.

B. Concentrator Processing. The major processing functions of the concentrator in NADIN I are as follows and are chiefly determined by the access line over which a message is received. The concentrator will be programmed to add certain fixed information to messages originating at specific terminals. Items that may be added are message priority, type, originator and addressee, individually and in any combination. The concentrator will also check the end of the message received to determine whether the correct end-of-message code was included. If not, the concentrator supplies the appropriate characters. The concentrator has the capability to convert the code and format of incoming messages, if a change is needed. For each message frame passed to the switch, the concentrator adds communication control information, including frame accounting information, a sequential message number, a key to the message code and format as transmitted, an indication as to whether the frame belongs to an information-message (intended for delivery to a user) or is a network management message. The communication control information with messages arriving from the switch indicates the subscriber access line to which the message is to be delivered and, for multi-point lines, the subscriber or subscribers to receive the message. The concentrator program recognizes the code and format used by each of the subscriber circuits and, recognizing the code and format in which the message was received, makes the conversion, if appropriate. The concentrator also selects the proper subscriber line and calls the addressed stations on the basis of the communication control information provided by the switch. A concentrator may also be programmed to supply the "boiler plate" in a message of fixed format that occurs frequently in the network. The originator of such a message need only include in the text he sends the identification of the text format and the variable information to be used, thus reducing the load on the network.

C. Switch Processing. NADIN I switching centers perform the bulk of message processing functions in a conventional store-and-forward mode of operation. The steps involved include the following:

Acknowledgement to Originator
Recording
Format Check and Edit
Routing
Code and Format Conversion
Output

Details relating to these functions are detailed in FAA Specification FAA-E-2661 dated January 4, 1977.

D. System Malfunction and Recovery. The NADIN design specifies a very high degree of system availiability and reliability. However, individual units of equipment can fail; intermodal circuits can fail, or not perform satisfactorily. A catastrophe such as fire or earthquake could put a switching center out of service. To protect against these events, the NADIN will utilize the following recovery procedures:

Intermodal Circuit Problems or Failure - A malfunctioning internode circuit will be removed from operational status by the responsible switch, either automatically or by manual action, so that transmission of traffic intended for that link will be delayed pending a change of status. Dialing equipment at the switch will be activated automatically under program control or by operator action and at the affected concentrator by remote control from the switch to initiate two temporary circuits, one for transmission in each direction to replace the circuit taken out of service. Operators at terminals equipped for dial service will initiate the replacement process; the replacement circuit will generally be established to the normal concentrator but could connect to another concentrator or to a switch. Switch configuration and routing tables will be changed to substitute dial-up ports for those used by the normal circuits. When maintenance services have restored the normal circuit to satisfactory condition, it will be returned to use, the switch tables updated, and the temporary dialed

circuit released.

Equipment Failure Including Complete Switching Center Failure - The network will be protected from the effects of most hardware faults by the redundancy built into the nodes. Strict maintainability requirements will insure that failed components will be repaired or replaced quickly enough that the probability would be acceptably low that a subsequent hardware failure in the same node would cause failure of the entire node. Nevertheless, a failure of an entire node could occur. If a concentrator is at fault, it is necessary to provide means for its terminals to have some other access to the network. Most terminals, particularly the low-speed ones, will not have such provisions. It will be necessary to use telephone or other means outside the NADIN to provide essential communications. Some terminals, however, will require uninterrupted NADIN access and will be provided with dial equipment. The operators at such terminals will initiate a call to a designated alternate parent node, either a nearby concentrator or a switch, which will serve the terminal until the normal parent node is returned to service. If a switch fails, the concentrators and external systems normally dependent on it will be picked up by the other switch by dial-up circuits. Dial-up calls will be normally initiated by the surviving switch. Each switch will have enough spare input/output channels and modems to serve the entire network in this manner. Routing tables and other operating software will be modified automatically in response to a single command by the switch operator and will be similarly restored to normal when the malfunctioning node is returned to service.

Message Recovery - Each switch maintains sequential lists of messages transmitted to each terminal and system interface. Each message transmission includes the sequence number. Checking in the same manner as for its transmitted messages, a terminal will recognize a break in the sequence if a message processed by the switch does not arrive. The intended recipient then uses a service message to request retransmission of the message corresponding to the missing number. In most cases, the response will be automatic. In others, depending on the message type and identity of the terminals involved, the request may be referred to an operator.

E. Data Recording and Journalling.

Circuit Related Data - Each switch will continually count the number of messages and characters transmitted and received over each circuit in its segment of the network. This count, averaged over a suitable period of time, will provide a measure of the loading of each circuit and, aggregated by node, the throughput of each node. This information will be recorded for each circuit at the prescribed intervals so that a record is preserved of the varying activity of each circuit throughout the day. These records may pertain to components and data paths within the nodes as well as to the internode circuits. In addition, a record will be maintained of the number of frame retransmissions required per interval and, consequently, the error rate of each circuit. Analysis programs will display for the operator the record of these data collections and simple derivations from the basic data, such as averages over longer periods and maxima and minima. Suitable alarms will notify the operator when established limits on significant parameters have been exceeded.

Message Related Data - Every message of designated types will be recorded completely. The recording will be retained for a relatively short period in fast-access storage to provide a quick basis for retransmission, should that become necessary. Longer retention, on a slower-access medium, will be provided for some, perhaps all, of the message types for which retransmission is provided, in order to make such messages available for later administrative use, as in connection with investigation of air traffic incidents. Partially extracted from the total recording and partly supplied by recording of other switch actions will be journal data. Journal data for messages of types not subject to total recording will be recorded. This data will include such characteristics as the identity of the originator and of all addresses, the type, the precedence designation, the time of receipt and other steps in the processing, and the message length. The journalling procedure will be carried out only when designated by the switch operators on a selectable basis. The analysis of journalled data will be used in adjusting the network for optimal response to current requirements and in determining the trend of requirements that the network must satisfy in the future.

SUMMARY AND REFERENCES

The major effort in the ground-ground data communications area is the modernization and consolidation of FAA's heretofore discrete data transfer networks into a single common user network called the NADIN. It will provide an integrated digital communications network to support domestic and international air movement activities. When completed, the NADIN will provide a fully integrated ATC ground-ground data network that is more economical and efficient than independent systems. The NADIN will provide for a high degree of reliability, flexibility and expandability and can be expanded as requirements dictate. The initial basic system will become the cornerstone of all FAA digital data communications and enhancements will continue to provide the total system serving the 1980's and 1990's.

ACKNOWLEDGEMENT

The author, A. K. Kingsley, wishes to thank his co-workers, C. E. LaRue, D. G. Rhoades and J. H. Yevonishon for their contribution on the NADIN design, specification and technical

documentation.

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2. FAA Form 9550-1, AT-30-7 dated July 1, 1971 and FAR 6180.1 dated January 10, 1972.

3. Report No. FAA-RD-74-200 entitled "Network Architecture of National Airspace Data Interchange Network (NADIN)" dated October 1975.

4. Production specification for a National Airspace Data Interchange Network (NADIN), FAA-E-2661, dated January 4, 1977.

5. FAA specification 2661 Appendix F, dated January 4, 1977.

6. ICAO Doc. 9203, ADISP/7, 1977, Recommendation 2/4 and 3/1.

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VOICE SWITCHING AND CONTROL SYSTEM
FOR FAA VOICE COMMUNICATIONS

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Biography

Leo Gumina is the program manager of one of the major programs designated by the Federal Aviation Administration (FAA) Administrator for intensified management. Prior to being designated Radio Communication Control System (RCCS) program manager he spent two years on the Wind Shear/Wake Vortex program office staff where he was responsible for development of ground systems for wind shear detection, and two years with the Microwave Landing Systems (MLS) program office system engineering division. He joined the FAA in 1974 after spending ten years in the U.S. Navy's automated control and landing system program office. Mr. Gumina holds a BSEE from Marquette University.

ABSTRACT

In house and contractor supported activities are being employed to develop and refine the requirements and technology for development of a new voice switching and control system for the FAA communication system. The broad scope and objectives of these tasks are listed with specific emphasis on the study of alternative switch architectures. The methodology used to assess the merits of combining or leaving uncombined the Radio and Interphone subsystems and their functional elements of the communication switching system is discussed. The impact of insuring that the principal competing technologies are suitable for the switch sizes and architectures is reviewed. The general schedule for implementing the switching system development is provided.

BACKGROUND

The mandated function of the Air Traffic Service (ATS) is to provide for an orderly flow of aircraft through the established air route structure in a safe and efficient manner. Key to successful accomplishment of this mission is the air traffic controller who is responsible for flight progress control, flight path conflict resolution, severe weather avoidance and other actions deemed necessary to insure safety of flight. To accomplish this mission the air traffic controller, whether located in a center, terminal or flight service station, is provided with various aids including an extensive, many faceted communication system through which he conducts the activities for which he is responsible. This provides the controller with access to rapid, uninterrupted communications with aircraft under his control as well as reliable communications with other controllers and organizational elements within and outside his immediate environment.

The present voice communication system which is intended to accommodate the demands of the National Airspace Air Traffic Control System has evolved over the past four decades, generally in response to urgent short-term requirements. It is now apparent that the capacity and flexibility of the current system, although capable of meeting the requirements of todays manual and semiautomatic environment, is not sufficient to meet the traffic capacity and automated operation projected for the post 1985 ATC environment, nor does the present architecture allow for easy expansion to meet those needs.[1]

Additionally, the cost of maintenance of the current system, due to its vintage design employing vacuum tubes, mechanical relays and manual patch panels, is becoming prohibitive.

The current system consists of two totally independent systems: An air/ground (radio) system which is owned and maintained by the FAA and the ground/ground (interphone/intercom) system which is a leased facility. The number of major installations that contain air/ground and ground/ground voice communications are listed in Table 1. Key to improvement of the current system is a replacement of the outmoded switching and control system for radio and interphone communication.

To effect the greatest benefit these two independent systems should be replaced by a single system which utilizes modern solid state technology and achieves the following operational capabilities:

- Increase the speed of establishing communications between controllers and between controllers and aircraft.
- Increase the system flexibility from the standpoint of rearranging services and adding new services.
- Reduces the out of service time by automatic line restoral technique.
- Reduces the maintenance workload by use

of automatic monitoring and fault isolation techniques.

Facility Type	No. of Facilities
ARTCC (Foreign & Domestic)	25
TRACON	218
Towers	495
FSS	326

Table 1

Summary of Facilities*

*Based on ATS Fact Book, December 31, 1977.

Technical Approach: To achieve the general operational objectives, studies and minor development tasks have been initiated specifically to answer questions related to the basic technical feasibility and economic acceptability of a switch system replacement program. The studies include:

(a) a review, updating and documentation of the operational and maintenance requirements.

(b) a survey of currently available switching systems to assess the state-of-the-art of switching and control technology.

(c) a study to determine the technological feasibility of combining and/or integrating the interphone and radio subsystems of the ATC communication system.

(d) a cost benefit analysis to assess the economic advantages of replacement of the radio subsystem, the interphone subsystem and the combined system.

(e) a program to develop and evaluate techniques for in-band signaling to eliminate the need for conditioned Telco lines.

Combined Switching and Control: Significant in the formulation of the development program is the study to investigate and compare a system which combines the Radio Communication Control System (RCCS) and Voice Communication System (VCS) with totally independent RCCS and VCS subsystems.[2] A combined system is defined as a system using the same technology, techniques, and modular construction throughout. The combined system could include various degrees of consolidation or integration of functional elements, if analysis demonstrates that the integration is technically feasible and economically desirable.

The logistics and physical benefits of a combined system seemed obvious from the outset. Such a system would require less space within an operating facility, would improve the maintenance and training efficiency and should result in a significant reduction in spare parts costs.

To assess the technical feasibility of combining the two subsystems, a generic architecture for the combined and uncombined systems was established. This generic system included the seven major functional elements: (1) input/output interfaces; (2) call processing; (3) call preprocessing; (4) interconnect network; (5) maintenance interfaces; (6) position elements and (7) trunk circuits. Each generic architectural system had to meet the principal ATC communication interconnect requirements of: Radio, Intercom, Interphone, Support and Automatic call Distribution (ACD). Additionally, the combined configuration(s) utilized for the comparison with the uncombined system configuration could not be biased by any one of the three candidate switch technologies under consideration, namely, Space Division (SDM), Time Division (TDM), of Frequency Division (FDM). While this latter restriction on the study prevents optimization of the combined configuration architecture, it does not eliminate from consideration any one of the possible approaches. It was felt that these options should be available to proposers for the system development phase. The resulting generic system architecture is shown in Figure 1.

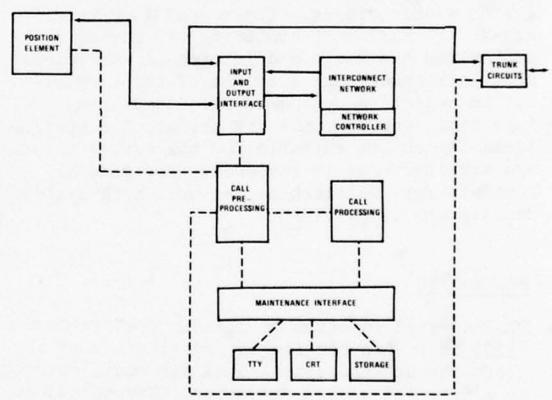

Figure 1
Switching System Architecture Basic (Generic)

A review was made of the competing techniques to determine if functional elements were sensitive to the switching technology employed.

From the review, the following general conclusions have been drawn:

- An interconnect network can be implemented in any one of three basic technologies or a combination of technologies.
- Optimum network structure or technology is dependent upon the unique requirements of the switching application. Optimum network technology is current state-of-the art

dependent and will vary as component technology advances.

Given a specific network structure certain technologies will likely have a distinct economic advantage although the basic switching requirement may be handled equally well by all three basic technologies.

Once it had been established that an acceptable switch system, albeit not optimized, could be developed with any of the available technologies an analysis of various alternative configurations for a NAS/ATC communication system was undertaken. As an initial step, a baseline system was developed employing an architecture in which major functional elements are totally uncombined, Figure 2.

personnel dictated a design approach which consolidates the maintenance elements.

Trunk elements consolidation can potentially offer a technical/economic advantage through the application of a universal trunk concept. Functional modules could be designed to a common baseline requirement permitting interchangeability of modules to be affected using a single, properly designed, prewired housing assembly. Various trunk circuits are interfaced by merely inserting the appropriate complement of functional modules into predetermined locations within the housing assembly. However, since the consolidation of trunk elements is not considered a significant influncing factor in the decision to combine or leave uncombined the RCCS and VCS no further analysis of the detailed merits of a universal trunk concept was done.

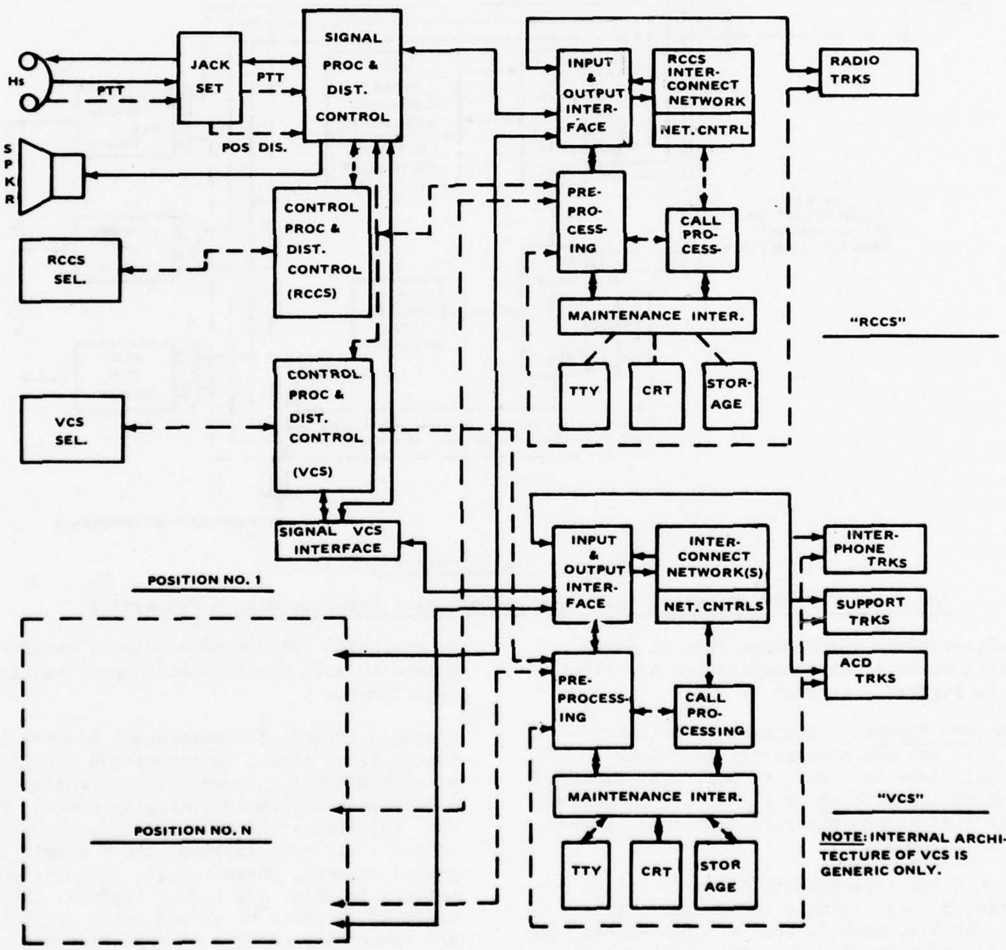

Figure 2 Umcombined RCCS/VCS Configuration

Because of limits on physical space in the operating environment and human factors consideration there is an immediate advantage to combining or integrating the position equipment of the two subsystems. Similarly, the orderly monitoring, surveillance and maintenance of the system with efficient utilization of maintenance

Two system elements remained to be assessed as candidates for integration in architectural structures of the system configurations: the interconnect functional element and common control (call processing/preprocessing) element. There are four viable alternatives structures which can be derived with the remaining elements.

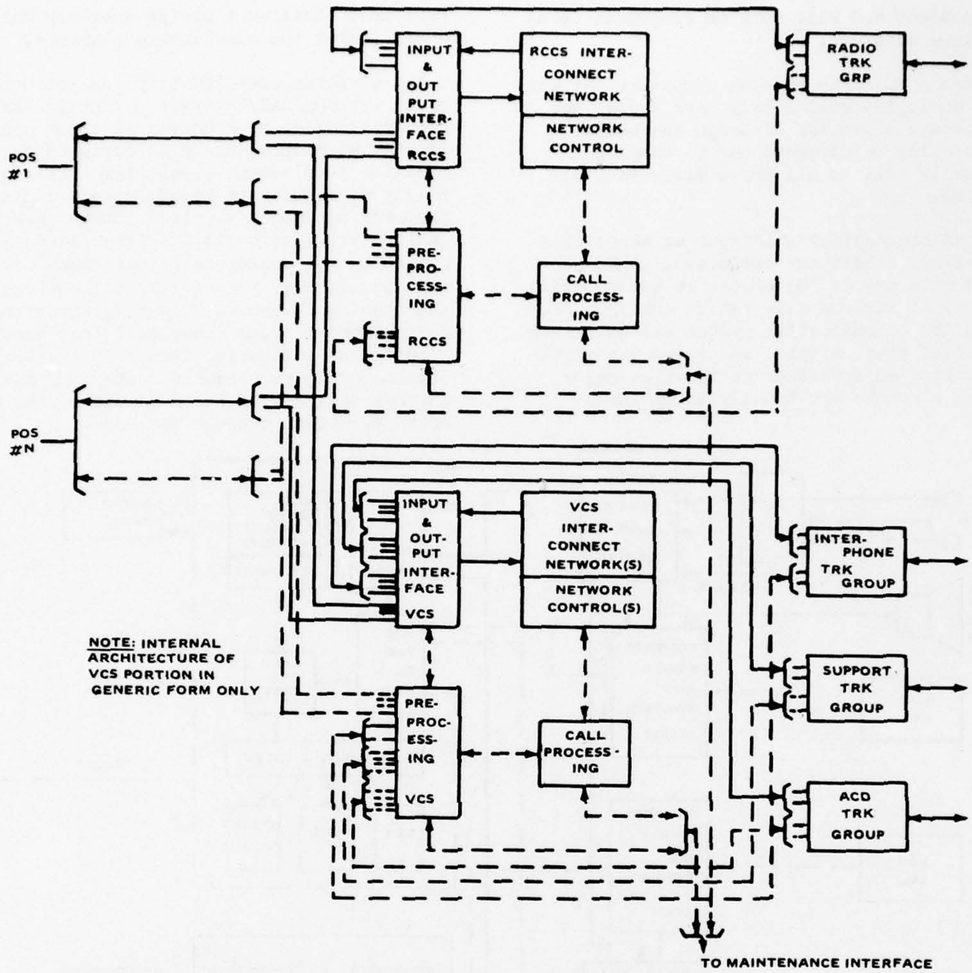

Figure 3 Alternate # 1

Combined RCCS/VCS (Separate Interconnect Networks; Preprocessing & Processing

These alternatives which range from no further consolidation to total consolidation are illustrated in Figures 3 through 6.

Interconnect Element: Whenever consolidating two or more but not necessarily identical functional elements, the more stringent parameters of design of both or all of the individual elements will govern the resultant consolidated functional element.

Hence, when two interconnect networks are to be consolidated into a single integrated interconnect network, such factors as grade-of-service and signal transmission/reception quality are dictated by those requirements in either individual network which are greater. The radio portion of the system requires a nonblocking interconnect network, whereas the interphone/intercom portion is somewhat less stringent in that blocking is permitted and specified by the required grade of service (e.g., P.001). Therefore, the consolidated interconnect network would be required to meet the more stringent, nonblocking requirement.

A second effect of interconnect network consolidation is to create an integrated functional element which far exceeds the consolidated inlet/outlet path access availability needs. That is, when two separate interconnect network functional elements are consolidated into a single integrated element, there results an interconnect network in which all inlets (whether they be assigned to radio or ground voice communications) are inherently capable of accessing any or all outlets (whether they be assigned to radio or ground voice communications). This unnecessary (and unwanted) overdesign is unavoidable and requires that additional capability be built into the common control to guard against establishing nonrequired inlet/outlet interconnect path connections.

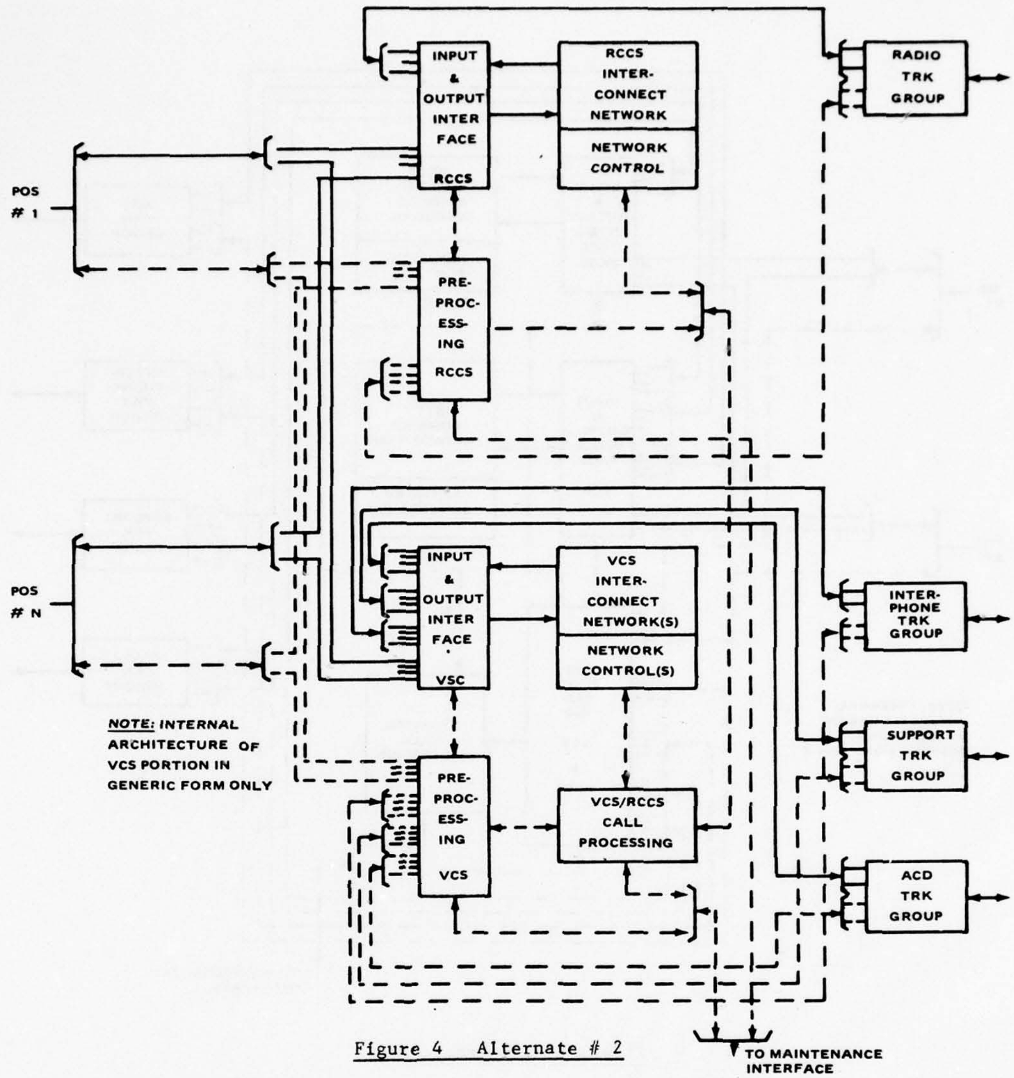

Figure 4 Alternate # 2

Combined RCCS/VCS (Separate Interconnect Networks; Preprocessing Only)

Moreover, the resultant integrated network contains far more hardware content than is necessary (if each element were separate), thus adversely impacting the economic and reliability merits of the system.

The following example illustrates the hardware complexity introduced by consolidating two interconnect networks.

For analytical simplicity, it is assumed that there exists the requirement of two independent service needs (radio and ground-to-ground voice) each of which required an interconnect network of the same size, and is further assumed that the number of inlets is equal to the number of outlets for both service needs.

For the purpose of this analysis the interconnect networks were developed in SDM technology and the measure of relative size will be the number of crosspoints required to configure each respective interconnect network. SDM was selected for this analysis not to indicate any particular preference for this approach but because of the relative ease with which a quantitative comparison of competing configurations can be made. It has been shown [3] every SDM three stage switch of the type used in the analysis has a TDM equivalent. In addition, a switch which employs an FDM technology can be considered equivalent to a SDM switch with the radio frequency channels substituted for connecting links of the SDM switch.

A three stage array for both the consolidated, Figure 7(a) and separate, Figure 7(b), configuration has been selected for this illustration since it is not only convenient from an analytical viewpoint, but is realistic in the sense that it is probably the most satisfactory multistage approach for satisfying the interconnect

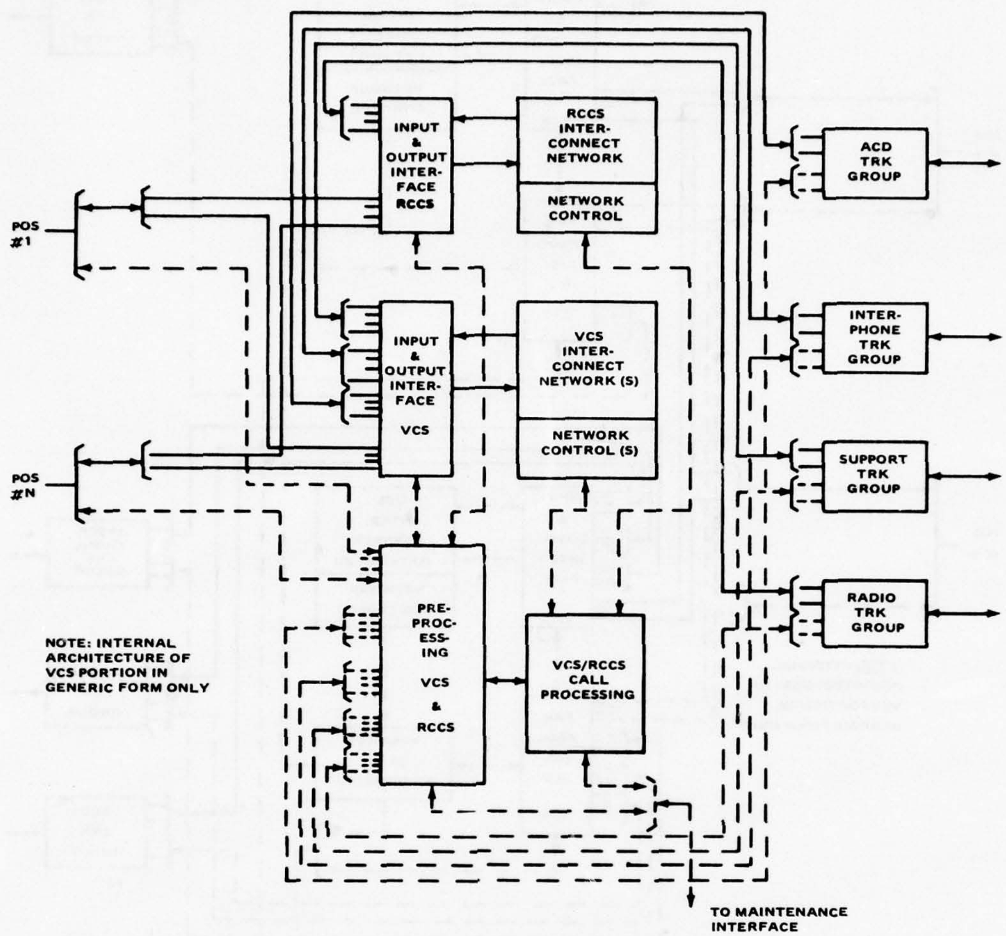

Figure 5 Alternate # 3

Combined RCCS/VCS (separate Interconnect Network Only)

requirements of a system such as that hypothesized in this example. As can be seen in the figures, inlets (M) and outlets (M') are subdivided into groups (N and N') which have access to associated interconnnection links.

These links are interconnected by the secondary stage to form a complete inlet to outlet connection. It has been shown by Clos[4] that the illustrated network is nonblocking when the number of interconnection links equals or exceeds 2N-1, where N is the number of inlets or outlets in the primary group. The configurations were sized for the number of crosspoints to satisfy a broad range of interconnect requirements. The results of this sizing analysis is summarized in Table 2.

In Table 2, columns 1 and 2 indicate the number of input and output terminations required for the total system requirement. This is the consolidated input/output requirements for both portions of the system. Column 3 indicates the number of crosspoints required if the consolidated interconnect network is constructed in a multistage (3) array configuration. Column 4 indicates the number of crosspoints required if two total interconnect requirements were satisfied by constructing two independent networks (one for RCCS and the other for VCS).

It is evident from the analysis summary in Table 2, that in all cases, separate interconnect networks offer an approach which requires significantly fewer crosspoints than the alternate combined approach.

Common Control Element: The analysis of a common control cannot be done as precisely as that for the interconnect network. The difficulty with analysis of the control element is that varying degrees of consolidation can be

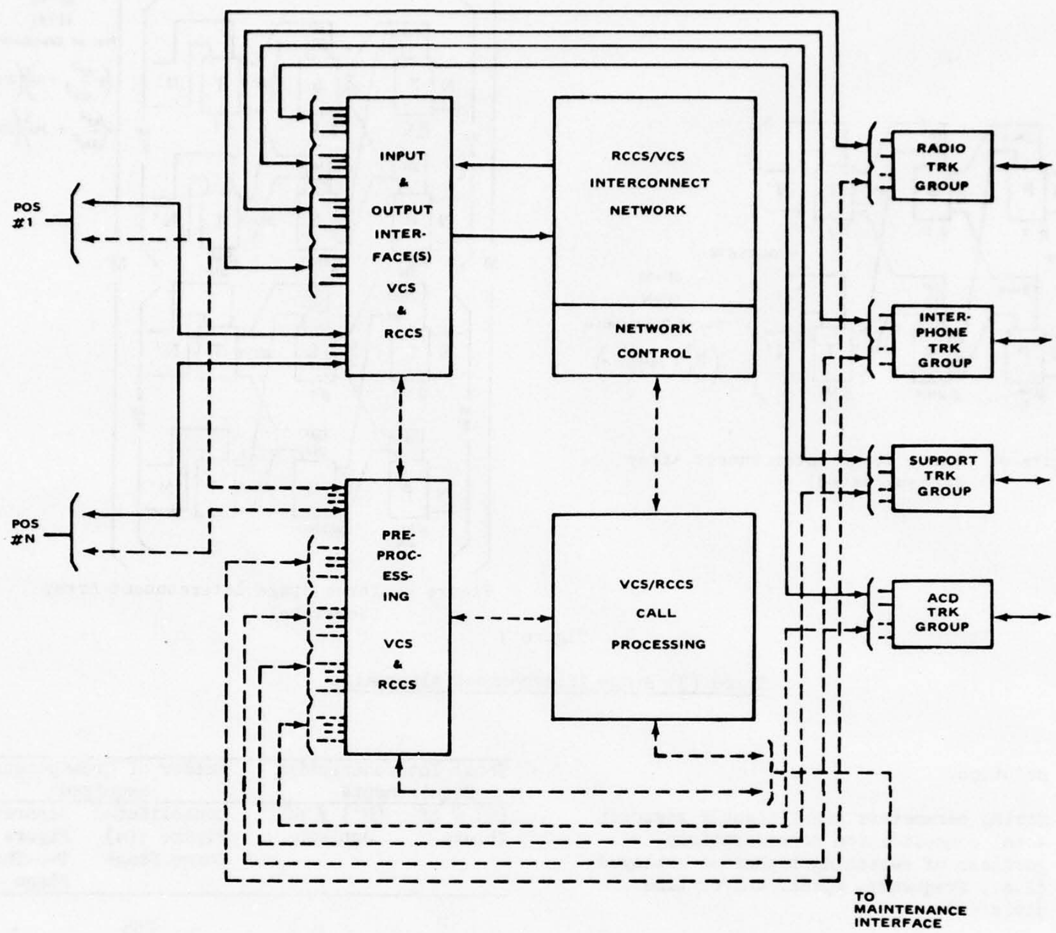

Figure 6 Alternate # 4

Combined RCCS/VCS (Totally Integrated)

applied to independent functions increasing the number of potentially viable alternatives.

The modern trend is switching system controls in the application of stored-program control which holds out the promise of greater operational flexibility. However, if the degrees of flexibility implemented into complex switch system is analyzed, it becomes evident that stored programs may be so complex and interrelated that it is difficult to implement changes. It is also apparent that a number of attractive alternatives to the stored program exists. Integrated circuits could be used for implementing some functions of the switch control with inexpensive and reliable hardware. There exists a delicate balance in applying techniques for structuring a control system. A single technique may not provide the most technically benefical nor cost effective approach. Rather a distributed control system architecture making best use of whatever technique is most suitable for each specific subfunction appears to be a more attractive approach.

Although the studies conducted to date have not addressed all the pertinent factors and will require more indepth analysis of system design options, the following general conclusions regarding combination of radio/interphone/intercom are considered significant and will influence the direction of the switching and control system program.

- Combined structures embody both logistic and physical enhancement properties for a system design.
- Within a combined structure, total integration of functionally similar elements, associated with the individual system portions may not offer the best technical

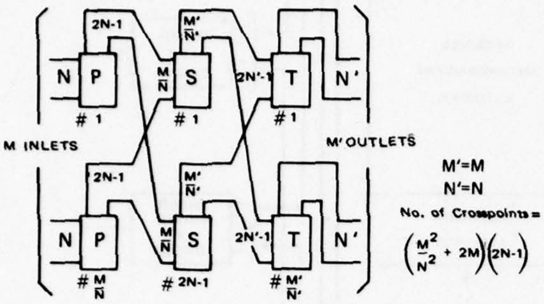

Figure A. Three Stage Interconnect Array (Consolidated)

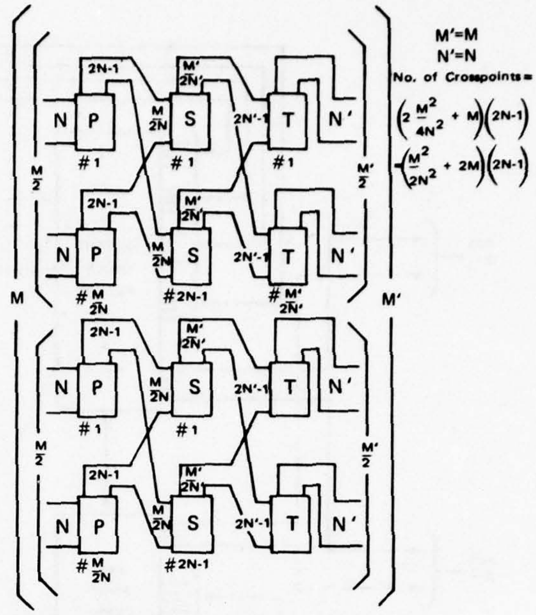

Figure B. Three Stage Interconnect Array (Separate)

Figure 7

Three (3) Stage Interconnect Alternates

solution.

- Sizing parameters significantly restrict total consolidation considerations, regardless of switching technique employed (i.e., frequency, space, and/or time division).
- Within an architectural structure of a five (5) major element configuration (namely: position, interconnect, control, trunk, and maintenance facility), consolidation of position and maintenance facility elements alone offers immediate and obvious technical and cost benefits.
- A compromise structure of control techniques (i.e., stored program and wired logic) coupled with a decentralized common control architecture (thereby reducing software oriented developments to manageable efforts) potentially offers the most technically beneficial approach for the control element organization.

SUMMARY

The studies identified above and particularly the study on combining subsystems are being used to formulate and scope a program for development of the replacement switching and control system. It is projected that our program planning will be completed in early 1979. A detail set of engineering requirements will be developed from an approved and coordinated operational requirement and will be used to solicit development proposals in 1980. As our studies indicate that no technological breakthrough is required to meet our program objectives, a development

Total Interconnecting Requirements		Number of Crosspoints Required	
(M) # of Inlets	(M') # of Outlets	Consolidated Figure 7(a) Three Stage	Separate Figure 7(b) Two-Three Stage
8	8	255	-
16	16	540	510
32	32	1,200	1,080
64	64	2,880	2,400
128	128	7,680	5,760
256	256	23,040	15,360
512	512	76,800	46,080
1,024	1,024	276,480	153,600
2,048	2,048	1,044,480	522,960

N * N' = 8

Table 2

Interconnect Network Sizing Comparisons

program containing a limited production quantity is a viable alternative for early implementation of the system. A decision on this matter will be made as more facts are developed.

REFERENCES

1/ Integrated National Airspace Communication System (INACS) for Support of Air Traffic Control Operations in the 1980's and 1990's, Operational/Maintenance Requirements FAA-INACS-661-221-OR July 11, 1975.

2/ Combined Radio Communications Control System and Voice Communication System Study, DOT FA78WAI - June 78.

3/ "Space-Time Equivalents in Connecting Networks," International Conference on Communications, 1970.

4/ "C. Clos," "A Study of Non-Blocking Switching Networks," Bell System Technical Journal, March 53.

AIRPORT GROUND PROGRAMS

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BIOGRAPHY

Herman D'Aulerio is Chief, Airport Safety Section in the Airport Safety Branch, Airport Division, of the Systems Research and Development Service. He has held this position since he came to FAA headquarters in 1968 from the Naval Air Systems Command. Prior to 1962, when he first entered public service with the Naval Air Systems Command, D'Aulerio worked for the Allied Chemical Company. He is a graduate of the University of Oklahoma (1951) BSME and is professionally registered in the State of Pennsylvania. D'Aulerio is responsible for the Grooving and Runway Traction section of this paper.

Eugene H. Hall is Chief, Facilities Section in the Airport Pavement and Facilities Branch, Airport Division, of the Systems Research and Development Service, a position he has held since Winter of 1976. He brings to this position a background in program management at both headquarters and field levels. He came to FAA headquarters in 1959 from its Central Region, where he first entered into public service in 1956. Prior to that, Mr. Hall worked in private industry for Westinghouse, Ford Motor Company, and the Kansas City Power and Light Company. He is a graduate of Kansas State College (1942) in the Electrical Engineering specialty and is professionally registered in the state of Missouri. Hall is responsible for the Visual Guidance Lighting Systems section of this paper.

Melville L. King is Chief, Airport Pavement Section in the Airport Pavement and Facilities Branch, Airport Division, of the Systems Research and Development Service, a position he has held since Spring of 1977. King came to FAA headquarters in 1964 from its Pacific Region, to which he had transferred in 1957 from the Pearl Harbor Naval Shipyard. A General Engineer for over 17 years, and an Electircal Engineer for 10, he graduated in the Electrical Engineering specialty (Communications Option) from Oregon State University (1951). King is responsible for the Airport Pavement section of this paper.

Hisao Tomita is a Civil Engineer in the Airport Pavement and Facilities Branch, Airport Division, of the Systems Research and Development Service. He has been responsible for managing R&D projects on pavement design and evaluation, pavement materials and construction methods since coming to FAA in 1973. Prior to 1973 he was with the Navy's Civil Engineering Laboratory for 15 years doing R&D work on airfield pavement design, evaluation, materials, and aircraft-airfield interaction. He holds a Bachelor's degree in Civil Engineering from Purdue University and a Master's degree in Civil Engineering from Texas A&M University. He is professionally registered in the states of California and Maryland. Tomita is responsible for the NDT section of this paper.

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ABSTRACT

Federal Aviation Administration research and development activities supporting airport ground programs are funded from the User Tax Trust Fund established by the Airport and Airway Development Act of 1970 as amended. Activities are directed toward airport safety, design, pavements, facilities, and weather. Progress is reported for Visual Guidance Lighting Systems, Grooving and Runway Surface Traction, Airport Pavements, and Nondestructive Testing of Airport Pavements.

Visual Guidance Lighting Systems have the goal of enhancing the safety of the aircraft pilot and passengers through provision of better information during approaches, landings, takeoffs and taxiing. This, whether in darkness, inclement weather, or other periods of low visibility. The lighting aids are listed, and needed refinements of aids and criteria are discussed as are projects now underway to resolve those needs.

Grooving and Runway Surface Traction research also have the goal of enhancing safety. Enhanced safety is obtained through reduction of those factors which place the aircraft at risk. Cutting of grooves into runways to offset the possibility of hydroplaning is discussed as well as some of the problems which the grooving causes in turn. A need for an optimum grooving configuration of low cost but which minimizes damage to airplane tires is stated. Progress toward development of that configuration is described and schedules are provided.

Airport Pavement research on the other hand is directed toward the goals of increased capacity, more effective operations, and cost savings in construction, maintenance, and repair. The objectives of the program are listed as being an updating of existing criteria, development of new design, test and evaluation methodologies, and support of identified Airport Development Aid Program Requirements. The research organization to attain these objectives is shown and progress through early 1978 is summarized. Continuing work is described (although not in detail), and planned future work is mentioned. Overall schedules are provided and expected economic benefits are briefly discussed. Nondestructive testing of airport pavements is presented in detail as an illustration of research progress toward the goals of more effective operations and cost savings.

TABLE OF CONTENTS

BACKGROUND

In response to the Airport and Airway Development Act of 1970, the FAA airport research and development program was initiated in 1971. It has moved forward over the years into progressively more difficult work in the areas of airport safety, pavement, facilities, design, and weather. As the years passed, many projects were completed and the results published in over 50 research reports and made available to concerned users. Some of the results such as structural design of pavements for light aircraft, field compaction of bituminous mixes for airport pavements, etc. have been converted by FAA Advisory Circular into criteria, standards, guidelines, or other benchmarks for national use. Some other results yet require additional investigation and explanation before they can proceed along that route. However, the capability of adopting for national use those improvements shown effective by test and demonstration provides exciting potential for cost savings in construction, in repair, in more effective operations, in fewer delays, and in enhanced safety. Progress toward these goals can be reported through the whole spectrum of fire/crash/rescue, snow removal, noise control, fog dispersal, and many other projects. However, this paper reports progress toward research goals in only three areas: Progress toward the goal of enhanced safety is illustrated by the sections on Visual Guidance Lighting Systems and Runway Grooving and Surface Traction. Progress toward the goals of economy and more effective operation is illustrated by the sections on Airport Pavements and evaluation of them by Nondestructive Testing.

SECTION I - VISUAL GUIDANCE LIGHTING SYSTEMS

INTRODUCTION

The basic scope of this program is the visual guidance lighting systems for airports that provide the necessary information for aircraft operation during approach, landing, take-off, and ground movement. Also included in the scope is identification of obstructions or hazards to aircraft.

The major aids or facilities in the program area are:

(1) Approach Light Systems (ALS)*

(2) Visual Approach Slope Indicators (VASI)*

(3) Lead-In Lights (LDIN)*

(4) Runway End Identification Lights (REIL)*

(5) Runway Lights

(6) Runway Markings

(7) Taxiway Lights

(8) Taxiway Routing and Directional Control

(9) Signs and Intersection Control

(10) Hazard Lighting and Marking of Tall Towers and Overhead Cables

PROBLEM DEFINITION

The first general objective is to improve and refine the visual aids as needed to increase the safety and reliability of aircraft operations under lower visibility conditions.

The second general objective is to provide the visual aids necessary to improve the efficiency of the pilot in guiding the movement of his aircraft off the runway and through the taxiway network.

The third general objective is to reduce the costs of establishing and maintaining these visual aids so that they will be cost effective at the smaller airports.

* These systems layouts are shown in Figure 1.

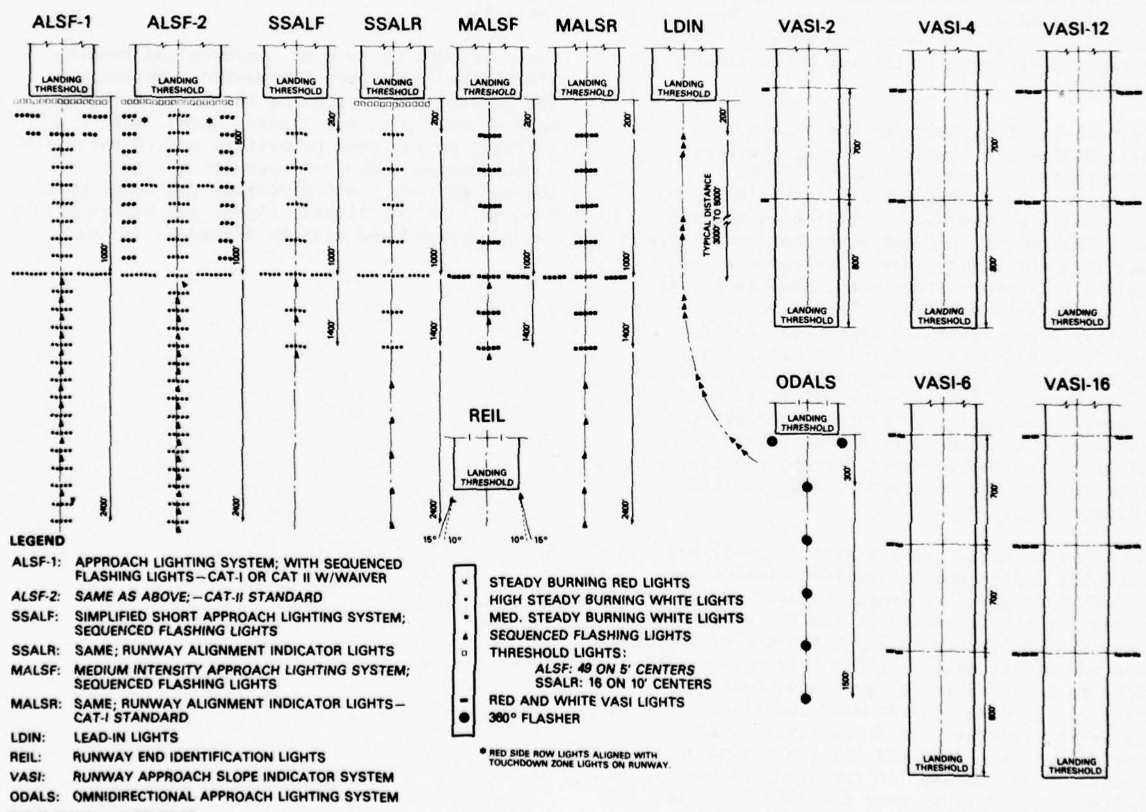

FIGURE 1
Visual Guidance Lighting Systems

BACKGROUND

In the present Approach and Runway Lighting systems, monitoring techniques provide only an indication of the total number of lamps not burning.

The location of these lamps in the system needs to be determined to assess whether the system provides the pilot adequate information to complete a safe landing, e.g., a complete 5 lamp bar being inoperative would be considered a system outage but if the 5 lamps are distributed over 5 bars the system would be considered adequate. The present technique requires an on-site inspection to determine where the lamp outages are. Additional R&D is needed to further refine those standards which define system outages.

Runway and taxiway marking standards are detailed in the appropriate Advisory Circulars; however, when paint is applied to airport pavements traction is affected, frost heave is accelerated, temperature effect on the pavement is induced, and the accumulation of many coats of paint and tire rubber contribute to the debris on the runway. Improved standards and guidance are needed to determine the effect on minimums when markings are obliterated, covered by snow, ice, or tire marks. Potential savings are possible if runway markings could be reduced without sacrificing operational safety.

Approach light systems provide pilots with basic decision-making cues during the final approach to the airport runway. To be effective, these fixtures are installed to be essentially at the same elevation as the runway. This means that where the terrain slopes down from the runway these fixtures are installed on support structures, sometimes over a hundred feet in height. The agency has underway a program to replace these towers with frangible ones that will minimize the potential hazard in the event of short landings or overruns. A longer range effort is needed to develop or apply new state-of-the-art techniques such as lasers, fiber optics, and holography as replacements for those obstructions such as the ALS support and airport guidance signs.

The ALS with sequenced flashers (ALSF-1) was initially designated to provide guidance down through Cateogry I minimums (Figure 1). By increasing the intensity of the red and green lamps from 300 watts to 500 watts and by adding five additional white lights, this system was found to be suitable for guidance under Category II conditions at most locations. A new system was then developed which would provide guidance for Category I minimums at a considerable savings in installation costs and operation expense over the ASLF-1. This system was designated as the medium intensity approach light system (MALS). Threshold lights for the MALS are now being evaluated which are expected to provide an even better system.

New runway edge lights have been developed which provide improved guidance for non-precision approach operations. This was a new lamp and fixture which was incorporated into the system. Under the same effort a new high intensity runway edge light and fixture was developed which reduced the energy consumption by 50 percent without reducing the effective guidance.

TECHNICAL APPROACH

Because of the emphasis on improving facilities for air carrier services, problems facing general aviation pilots have received little attention. We have, however, in the last 2 years, initiated several projects aimed at improving aids for general aviation. A study to explore the state-of-the-art in very low cost VASIs is underway. The aim is to evaluate the effectiveness of those aids that are in existence and explore techniques to improve those aids that look promising. Since the majority of general aviation (GA) accidents happen during approach and landing, low cost landing aids would certainly improve safety at the thousands of GA airports. Investigation of better and more economical ways of marking and identifying airports with unpaved runways is underway at our NAFEC facility.

These efforts because of manpower and funding limitations have been fragmented. We are at the present time reviewing the total development program plan for lights, signs, and markings to reassess priorities and to establish a coordinated technical approach for meeting the objectives. An Engineering and Development Program Plan for lights, signs, and markings is being prepared and will be issued early next year.

SECTION II - GROOVING AND RUNWAY SURFACE TRACTION

INTRODUCTION

It has been established by NASA experiments and operational experience that grooved runways significantly prevent hydroplaning on wet runways.[1] The FAA has approved runway grooving as a means to reduce the hazard of aircraft run-off caused by wet slippery runways.[2] However, grooving has not been widely accomplished; possibly because of high cost, runway down time, the need to remove expensive installed material and to repeat this action after each overlay, and uncertainties as to possible detrimental after effects involved in grooving runways. This program is designed to increase the number of runway grooving installations, by determining the optimum cost-effective groove configuration; that is, the groove configuration that would be least costly to install and still provide acceptable performance. Acceptable performance includes the deleterious effects grooving has on the pavement and tires as well as the beneficial effect of providing traction for the aircraft on wet runways.

PROBLEM DEFINITION

An optimum groove configuration is required with the increasing number of runways being grooved. A standard acceptable to the aviation community which will minimize installation costs and the cutting effect of dry grooves on aircraft tires needs to be developed.

BACKGROUND

The FAA, USAF and NASA conducted programs to alleviate the problem of hydroplaning on wet runways. As a result, it was found that grooves in the runway significantly prevent aircraft from hydroplaning. NASA conducted a test program at Wallops Station, Langley Research Center, VA, and determined that the most effective groove configuration to reduce or eliminate hydroplaning is one with grooves 1/4 inch wide x 1/4 inch deep, spaced on 1 inch centers.[1] However, it has been reported that this configuration causes excessive tire wear and tire damage; it has caused severe chevron shaped tire cuts.[3] NASA also conducted freeze-thaw tests and found that grooving did not cause any detrimental effects on pavements from freezing and thawing.[1] Despite the fact that grooving significantly reduces or eliminates hydroplaning and that a sizable portion of the cost of installing grooves in runways is subsidized by FAA ADAP funds, relatively few airports have grooved their runways. The reluctance of more airport operators to groove their runways may be attributed to:

(1) The initial high costs of cutting grooves and recurring costs after resurfacing.

(2) Airport closed time for installation.

(3) Possible detrimental after effects such as:

(a) greater rubber deposits

(b) greater difficulties in removing the rubber

(c) decrease in pavement life (cracking and spalling)

(d) excessive wear and possible damage to aircraft tires

These factors are being considered in determining the optimum groove configuration in the research program now being conducted by the FAA at the Naval Air Engineering Test Facility, Lakehurst, N.J.

TECHNICAL APPROACH

Conduct a test and evaluation program that will identify the most efficient groove shapes and patterns for various runway pavement materials, will provide optimum traction under all weather conditions, will cause minimum damage and wear to aircraft tires, and can be easily and quickly installed at least cost. The tests and evaluations will be performed in such a manner as to provide criteria for establishing grooving standards.

Wheel braking, friction, hydroplaning characteristics, cost, and patterns of improved groove shapes as well as porous runway materials are being tested with respect to cost effectiveness and braking action. In this approach, chevron cuts, an improved groove shape and other candidate patterns will be tested against the current ADAP approved 1/4 inch by 1/4 inch groove on 1 1/4 inch spacings. In these laboratory tests, the most important variables such as speed, water depth, tire load, descent rate, etc. can be closely controlled. The Ships Installation at Naval Air Station, Lakehurst, N.J. is ideally equipped to perform this type of testing. It has five test tracks equipped with four-engine jet sleds and deadload test vehicles. A test track has been scheduled for this program and has the following capabilities to accomplish the test program.

Test Track Capacity

Jet sled/deadload (Figure 1) speeds up to 200 knots with speed control of ± 1 knot. The deadload capacity is 100,000 pounds.

Testing Requirements

Speed: to 150 knots

Loads: to 35,000 pounds

Record Instrumentation

Forty-eight channel, telemetry capability, instrumentation is available on the deadload, and all types of data printout and processing are available.

Parameters Recorded

Speed of Deadload

Speed of Test Tire

Time

Drag Force Tire/Wheel

Sink Rate

Vertical Tire/Wheel Load

Horizontal Tire/Wheel Load

Brake Pressure

Temperature

Test Apron (Figure 2)

The test section is 200 feet in length by 36 inches wide and is excavated at the end of and between the tracks. The test surface can be prepared with various materials (Portland Cement Concrete-PCC, Asphalt Porous Friction Course) and grooved with candidate groove shapes and patterns.

Deadload Control

A monorail installed at the end of the jet sled track and parallel to it is used to control functions of sink rate, wheel loading, brake application, etc. of the test wheel.

Deadload

The deadload can be loaded to more than 50,000 pounds; consequently, the aircraft test wheel (Figure 3) can be loaded to any known representative wheel loading. Two types of test rigs are being used with a Boeing 727 (49 x 17 type VII) aircraft tire. One provides sink rates 1.5 to 4.5 feet per second for spin up tests, and the other provides braking action for friction/hydroplaning tests.

Test Patterns

Candidate test groove shapes and patterns approximately 24 inches wide and 50 feet long are cut in the test apron producing a total of four test configurations per test path.

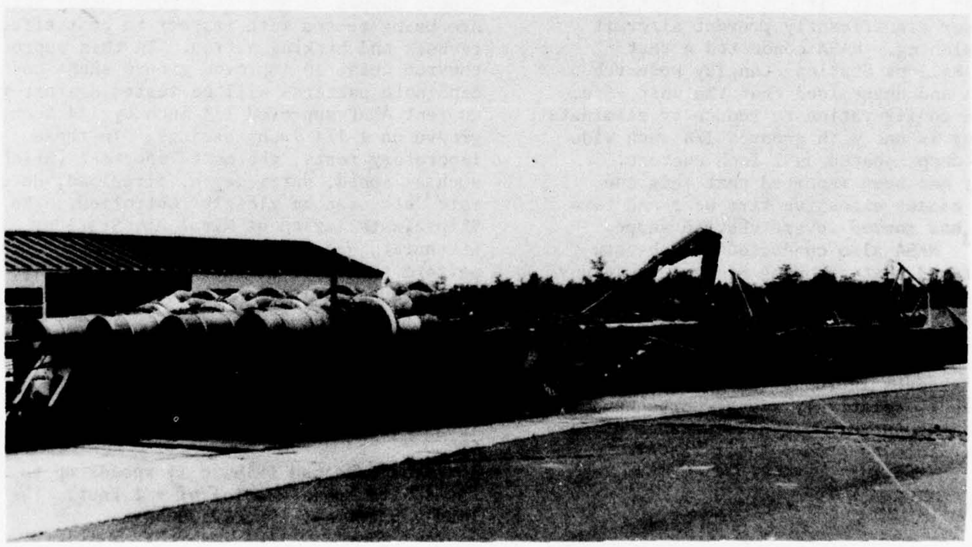

FIGURE 1

Jet Sled/Deadload

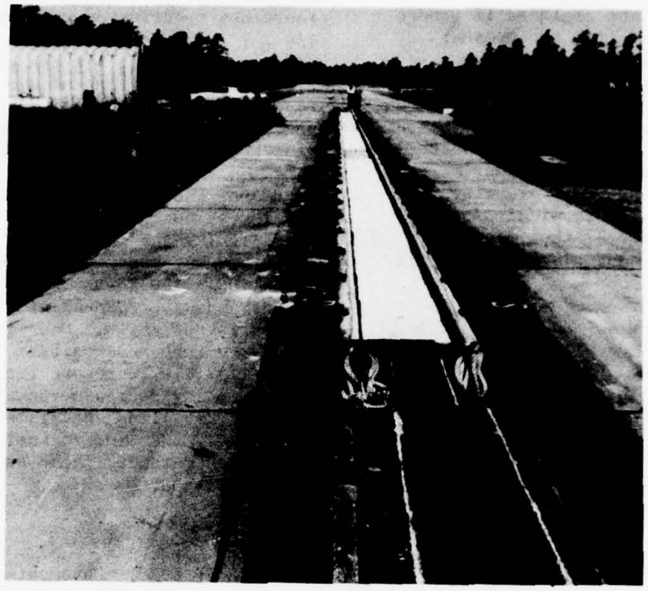

FIGURE 2
Test Apron

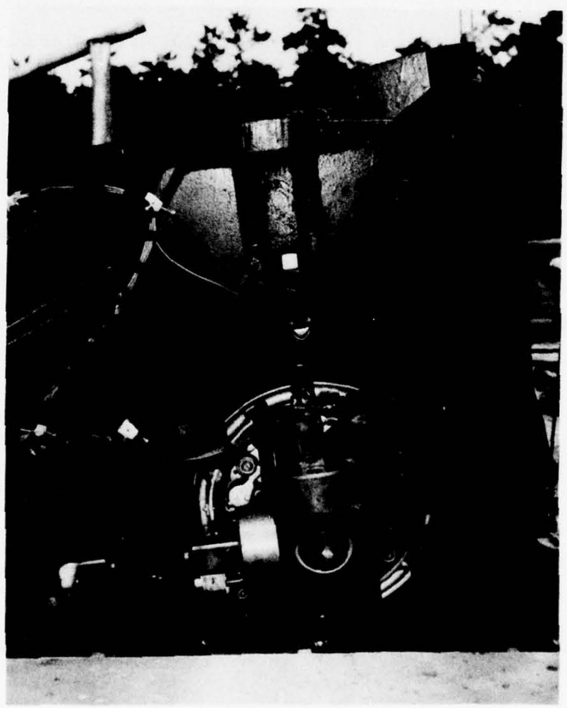

FIGURE 3
Aircraft Test Wheel

EXPECTED BENEFITS

Investigation into grooving costs indicated that greater cost savings could be realized if groove spacings could be increased from the present standard 1 inch spacing. Increasing the spacing would also decrease aircraft tire wear and reduce the tire cutting experienced with the 1/4 x 1/4 x 1 inch groove configuration. Lessened rubber accumulation and easier cleaning of the runways will result with wider groove spacings. It is hoped that grooving of runways will then become more widely accepted by airport owners and managers, thus reducing the hazard of hydroplaning and aircraft run-offs on wet runways.

Preliminary results, Figure 4, indicate that 3 inch spacings may provide acceptable performance. If so, a 30 percent cost savings per installation would be possible. Beneficial results may also be possible from Porous Friction Courses (PFC) or certain other pavements with grooves installed in the plastic state.

SCHEDULES:

(1) Interim Report - "Test and Evaluation Results of Grooves on Portland Cement Concrete (PCC)" - September 1978.

(2) Interim Report - "Test and Evaluation Results of Grooves on Asphaltic Concrete" - December 1978.

(3) Interim Report - "Test and Evaluation Results of Grooves Installed in the Plastic State" - March 1979.

(4) Final Report on "PCC, PFC, Asphaltic Concrete and PG Performances" - March 1980.

SUMMARY

We know that grooving reduces hydroplaning and increases traction on wet runways. The 1/4 x 1/4 x 1 inch groove configuration is most effective, however, it can cause excessive tire wear and cutting of aircraft tires at touchdown on dry pavements. Grooving does not have any detrimental effect on the pavement because of freeze and thaw cycles.

We do not know to what extent various groove configurations are effective in reducing hydroplaning and increasing braking action on wet runway especially at the higher speeds (from 100 - 150 knots). The critical landing speeds and water depths at which hydroplaning occurs is not known. Does grooving cause excessive rubber deposits? Are rubber deposits more difficult to remove from grooved pavements? Does grooving decrease runway life, cause chipping, spalling and cracking? Is there a less costly and time consuming grooving installation method? These questions are thus far unresolved.

REFERENCES

1. NASA SP 5073, "Pavement Grooving and Traction Studies," November 1968.

2. Advisory Circular 150/5320-12, June 30, 1975, "Methods for the Design, Construction and Maintenance of Skid Resistant Airport Pavement Surfaces."

3. FAA-RD-74-12, "Laboratory Method for Evaluating Effect of Runway Grooving on Aircraft Tires."

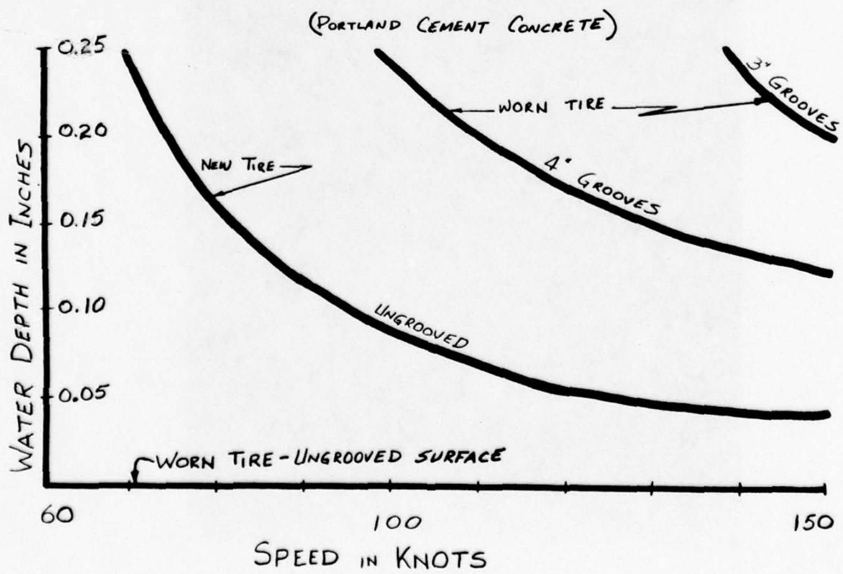

FIGURE 4
Hydroplaning Curves

SECTION III - AIRPORT PAVEMENTS

INTRODUCTION

For some years now the developing technologies of civil aircraft have imposed operating demands upon airport pavements that are met only at enormous costs in construction and maintenance. Weights of civil aircraft have grown progressively heavier; jets in the 300,000 lb. and 750,000 lb. classes are now common. The heavier wheel loads and higher tire pressures demand pavements of greater strength and longer life for more effective cost/benefit ratios. At the same time it has been necessary to lengthen the pavements and make them smoother, both at escalating cost. There are numerous examples where costly early pavement failures can be traced to lack of adequate technical data in the pavement structural design. In general, construction has been an empirical process where structural designs of proven adequacy for sets of known conditions have been extended, amplified, or otherwise modified, and then applied to meet new sets of demands in the hope the modified designs would work as well for the new conditions as the basic designs did for the old. If results were unsatisfactory, then other expensive experimentations were tried.

Neither airport operators nor construction contractors can realistically afford to experiment with new structural designs and applications. Construction practice tends to repeat earlier designs even if inadequate or grossly overstrength. The need for a Government sponsored Research, Development, Engineering and Demonstration Program was therefore recognized by the Airport and Airway Development Act of 1970 (public law 91-258) which authorized FAA to establish a continuing research program funded from the User Tax Trust Fund.

PROBLEM DEFINITION

General Objectives

The research program established in 1971, in response to public law 91-258 has three general objectives (see Figure 1):

The first objective was to upgrade pavement design criteria and construction standards based upon then-existent technology. This objective has now been met with the rapidly approaching completion of that phase of the program. Some 50 airport structural design interim and final research reports have already been published. Only a few remain to be put in final form before publication. The information developed to meet this program objective replaces and supplements the industry's original technology, which was derived mainly from extrapolation of military and highway flexible and rigid pavement criteria and from post World War II experience.

The second general objective is that of developing new design, test and evaluation methodologies which will be developed from basic research into theory, and then will be applied to airport pavement specifically designed for operating demands and requirements of both current and proposed aircraft. This second research program was begun in 1973, and in 1977 it produced a Layered Elastic Structural design technique with a confidence level approaching 70 percent. Subsequent research studies, analyses, and evaluations continuing under this program are expected to generate a confidence level nearing 90 percent to meet the future aircraft and airport requirements for the 1980's to the year 2000. It is intended that this structural design approach will be extended into a Universal Design and Evaluation Technique that can be rationally applied to assess the lifetime performance of any pavement structure, constructed with any material, and under any environmental condition.

The third general objective is to support sustaining engineering requirements as they are identified. These requirements may involve design criteria, materials, construction, evaluation, and tests. The work effort is usually directed toward short-lived, near term research responses to specific or unique engineering problems which arise during application of the general design theories.

TECHNICAL APPROACH

BACKGROUND

Recognizing that solutions to airport pavement design problems require a considerable effort, the FAA concluded it would be most effective to use existing research capabilities of other organizations to the fullest rather than to establish research laboratories of its own. Therefore, work is performed for FAA through contract with industrial groups or through interagency agreements with other government bodies.

Figure 2 shows how these various organizations interact and are melded into the FAA airport pavement research organization. Over the years, this organization has proven effective, has completed the research, and is moving forward with the projects shown below.

Completed Research

The completed effort deals with:

(1) current design criteria,

(2) materials and construction, and

(3) nondestructive evaluation by the Dynamic Stiffness Modulus (DSM) method.

SRDS Report FAA-RD-74-35, "Criteria for Airports Pavements - Final Summary Report" September 1976, provides a useful summary of research completed

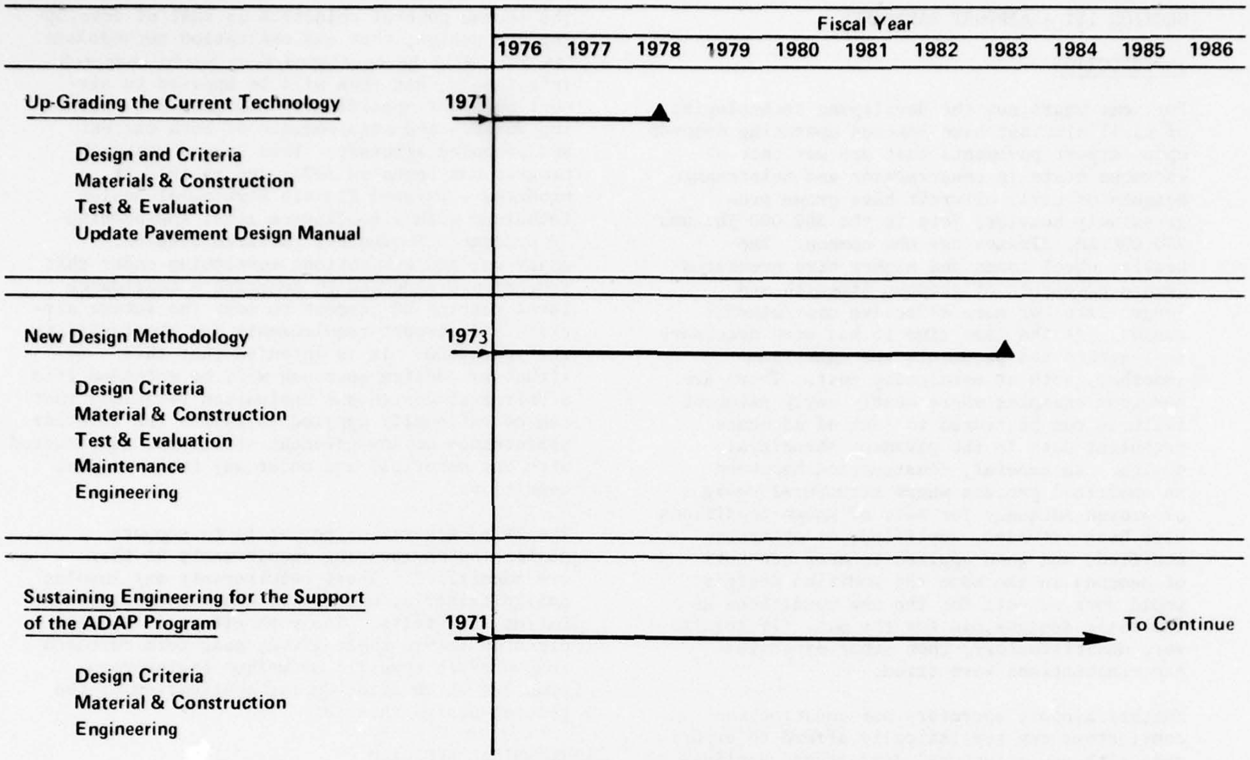

FIGURE 1
The Three Major Areas of
Airport Pavement R&D Concentration

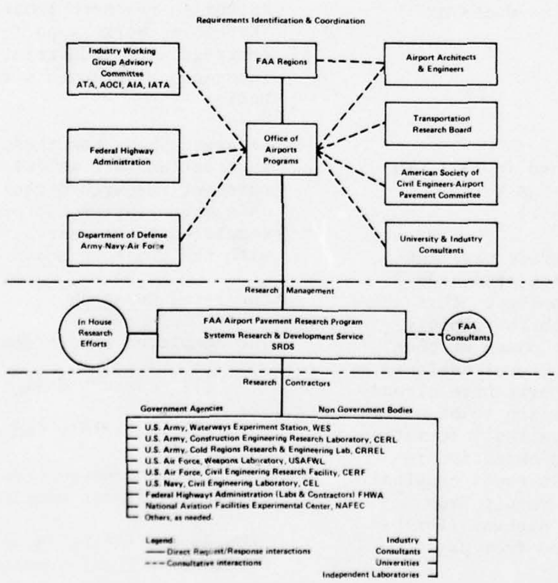

FIGURE 2
FAA Airport Pavement Research Organization

to that time. The specific objectives of that research are:

(a) Provide design guidance and criteria using current technology with available materials at reasonable cost for airport pavements to accommodate present and future aircraft loads for approximately 20 year service life.

(b) Develop pavement material and construction standards to insure that the design criteria are realized.

(c) Develop test methods and standards primarily using nondestructive testing devices for evaluating performance and load-bearing capacity of pavements.

(d) Provide methods for repairing and rehabilitating existing pavements and surfaces to improve effectiveness and extend service life.

More than fifty research reports have now been published in these areas. They are available to the public through the National Technical Information Service, Springfield, Virginia 22161. A list (List of Airport Pavements Reports 1972 - 1978) is available from the FAA's Airport Pavement and Facilities Branch (telephone (202) 426-9396).

Some of the more important reports published are:

"Field Survey and Analysis of Aircraft Distribution on Airport Pavement," February 1975, which discusses repetitious application of loads to pavement in terms of "coverages" representing the number of times a particular point on the pavement is expected to be stressed as a result of a given number of aircraft operations (passes). The study compared actual lateral distribution against theoretical distributions. It concluded that actual lateral distributions of aircraft traffic are much more nearly represented by theoretical normal distribution functions than by a modified uniform distribution function. Thus, pavements can be built more efficiently with a narrow, heavy keel section, and with the remaining surface of lighter and much cheaper construction.

"Nondestructive Vibratory Testing of Airport Pavements," April - October 1975, and SRDS Bulletin FAA-74-1, "Nondestructive Testing" September 1974, which report studies to develop test methodologies based on dynamic stiffness modulus and load carrying capacity. The studies resulted in acceptance by the FAA of nondestructive testing by the Dynamic Stiffness Modulus method.

"Aircraft Pavement Compatibility Study," September 1974, which analyzes trade-offs between providing sufficient flotation to accommodate the use of existing pavements or optimizing gear configuration for maximum aircraft payload against an increase in pavement strength.

"Steel Fibrous Concrete for Airport Pavement Applications," November 1974, and SRDS Report FAA-RD-72-119, "Construction of Fibrous Reinforced Concrete Overlay Test Slabs, Tampa International Airport, Florida," October 1972, which provide design criteria. Steel fibrous concrete pavement can be approximately half the thickness of reinforced concrete, but in general has a higher cost. Use of fibrous type concrete proved economically advantageous for at least two airports in the western United States.

Ongoing Research

Figure 3 is a summary schedule of the projects now underway or planned, and a brief description of each effort follows. Additional sustaining engineering to support ADAP projects will be included as it is identified.

Validate Layered Elastic Evaluation by NDT - A flexible pavement will be designed following layered elastic design principles and concepts developed previously. The pavement will be constructed at an air carrier airport, instrumented, and pavement parameters recorded under actual operation. These parameters will then be compared against theoretical values and the analysis used to prove validity of the design or to make improvements if needed. Rigid pavement will be field validated in later years.

Layered Elastic Design Procedures - Layered elastic design theory will be consolidated into a set of procedures to be used in designing airport pavement. It will include an instructional report on the design of pavements and include data on cumulative damage, differentation between performance of various material, strain criteria of bituminous concrete and the effects of subgrade variability on functional performance of pavements.

Expansive Soils Study - This is a continuing joint effort with the Air Force. Phases 1 and 2 are complete and concluded that tools are available to test and evaluate swell and predict subgrade heave but that additional research would be needed to transform those research tools into implementable design tools. Phase 3 was initiated this fiscal year (1978) and will develop soil suction measurements and analyze load-suction-volume change relationships. Correlations of various types of expansive soils in natural and stabilized conditions will be obtained through laboratory experimentation.

Frost Predictive Techniques - This is a continuing joint effort with the Federal Highway Administration and the Army. Phases 1 and 2 which cover theoretical and practical development of a mathematical model for frost heave prediction are nearing completion. Planning for Phases 3, 4, and 5 has been initiated. Phases 3, 4, and 5 will cover selection of sites for field testing, field site investigations, and validation of the field results against the mathematical model.

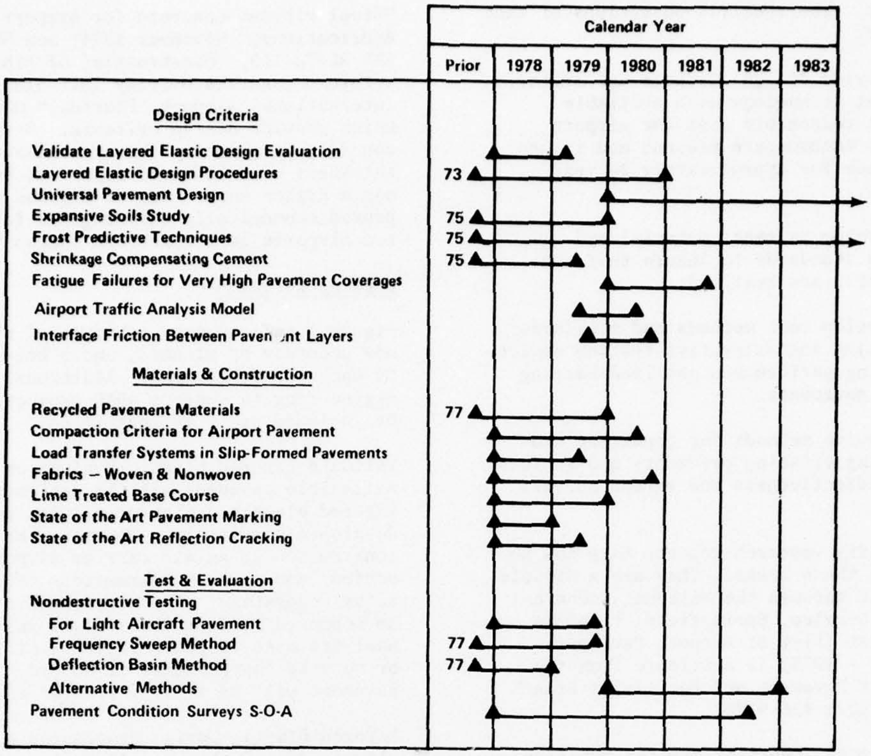

FIGURE 3
Research Engineering and Development Tentative Schedules
for Airport Pavement Projects

Shrinkage Compensating Cement - An on-going program of experimentation with shrinkage compensating cement will be completed. The objective is to determine whether shrinkage compensating cement in conjunction with fibre additives will produce a rigid pavement capable of being constructed with joints spaced at intervals up to 250 feet. A test bed will be installed at an operating air carrier airport. It will be instrumented and tested under actual operation. Data will be collected and the pavements' performance analyzed.

Fatigue Criteria for Very High Pavement Coverages - Pavement fatigue criteria are available only for relatively low "coverages". (Coverages represent the number of times a particular point on the pavement is expected to be stressed as a result of a given number of aircraft operations (passes)). Some airports experience coverages 100 times greater than the existing criteria which are limited to 2500. Accelerated testing of pavement will be obtained on a wheel track.

Airport Pavement Traffic Analysis Model - The data obtained during a previous study on aircraft traffic distribution over runways and taxiways during take-off, landing, and taxiing operations will be used to develop a mathematical distibution analysis model. The distribution analysis model will then be used to determine maximum stresses and pavement difficulties at various distances from reference points such as runway and taxiway centerlines. The model will consider 4 categories of air carrier airports:

Airports with DC-9/B-737 as the heaviest aircraft.

Airports with B-727 as the heaviest aircraft.

Airports with B-707/DC-8 as the heaviest aircraft.

Airports with B-747/L 1011 as the heaviest aircraft.

Interface Friction Between Pavement Layers - The various models for theoretical analysis of pavement (such as the Layered Elastic Model) assume either full friction (bonded) or no friction (unbonded) conditions between the various pavement layers. Actual friction obtained at the interfaces of the layers may be considerably different from the theoretical assumptions. Instrumentation will be developed and field tests will be conducted to measure actual friction conditions for incorporation of actual data with the analysis models. The resultant data and analyses will then be used to determine optimal construction procedures to be used; e.g., tack coat or other treatment of the interfacing surfaces between layers.

Recycled Asphalt and Rigid Pavement Materials - During FY-1977 work began on a study to determine whether asphaltic concrete could be removed, recycled, and reused in new flexible pavements. Work will be carried to completion and a new study for rigid pavements will be completed. In both studies, samples of old pavements will be obtained, reprocessed, and then reused as components of the new pavement. Criteria will be developed covering methods, processes, techniques, and performance characterisitcs.

Compaction Criteria for Airport Pavement - Base and subbase materials are compacted to provide stabilization and firm support for overlying layers of pavement. Currently used compaction criteria have been established by trial and error against laboratory determined values of maximum density at optimum moisture content. Values specified are often difficult to obtain. The influence of inelastic deformations on pavement layer density and stability will be studied so as to assess and revise compaction criteria if necessary. Currently specified values will be either validated or revised to yield optimum construction and operational use tradeoffs.

Load Transfer Systems in Slip-Formed Pavements - Keyed joints in rigid pavement have a history of unsatisfactory performance. However, the French Laboratory of Bridges and Highways has proposed a simple dowel repair that may prove feasible at low cost. The concept will be analyzed. If it is feasible, the methods to manufacture and install will be developed. In addition, many other types of joints in slip-formed pavements are being studied in an effort to determine which would prove most cost effective under a range of varying conditions.

Fabrics (Woven and Nonwoven) - Several brands of fabrics have properties which are advantageous in the construction of airport pavements. They have been considered for filter membranes, drainage membranes, bituminous pavement reinforcement, control of reflection cracking, expedient surfacing, etc. A literature search will be conducted to determine state-of-the-art applicability which will then be used to determine whether an RD&E effort will be needed to develop application standards for airport pavements.

Stabilization of Existing Soils - Test methods and techniques will be developed to determine if existing soil or subgrades at potential airport sites can be economically treated with stabilizers so that pavements can be placed upon them. Positive results will mean that importation of base course materials will not be necessary. The following project is a special case of this general project.

> Lime Treated Base Course - On site soils at several airports have been stabilized with lime so as to provide base courses at reduced construction costs. Pavements may or may not be performing satisfactorily. Evaluation is necessary to assure that satisfactory performance is continuing or to detect early signs of degration.

Airport Pavement Marking - A state-of-the-art review on pavement marking techniques and materials will be made. Library searches, reviews of ASTM, AASHTO, military specifications, federal specifications, and foreign standards will be completed. No testing will be accomplished, but performance, cost, durability, friction data and other characteristics will be collected, analyzed, and conclusions and recommendations developed.

Reflection Cracking - A state-of-the-art survey will be made to determine which methods are being used most successfully to control the reflection of pavement cracks into new overlays.

Nondestructive Tests - Nondestructive testing methods based on dynamic stiffness moduli have been developed and are now operational. Frequency sweep nondestructive methods of lower cost and wider applicability have also been developed but not yet proven; these new methods will be validated and published. At the same time, work will be carried forward on a Deflection Basin Method which offers even more potential based on lower cost equipment of greater portability. Nondestructive testing of pavements constructed for light aircraft (less than 90,000#) will be examined.

Pavement Condition Surveys - At present, field condition surveys are made to a variety of criteria. Responsible engineers may come to differing conclusions. A survey method is needed which can be used as a standard so that subsequent surveys can be related and pavement deterioration or improvements taken into account. Also, the standard pavement performance analysis method will allow airport authorities with several airports to compare predicted performances and to optimize maintenance, repair and rehabilitation priorities among them.

Future Projects - Some projects for which a need is known but data are not yet developed are:

> Optimization of Preventive Maintenance
>
> Improved Cost/Benefit Analysis Method
>
> Criteria for Rehabilitiation of Porous Friction Course
>
> Develop a Portland Cement Porous Friction Course
>
> Update Technology for Overlay Construction
>
> Develop Method to Arrest Time Deterioration of Pavements
>
> Investigate Runway Transverse Profile
>
> Determine Projected Pavement Life Following Incipient Failure Signs

Confined Materials for Light Aircraft Pavements

Additional Load Traffic Distribution Data

Universal Pavement Design

EXPECTED BENEFITS

Expected benefits are mostly economic although subsidary benefits will be realized through recycling of scarce materials, smaller energy requirements, reduced air pollution and the like. Expected economic benefits may perhaps best be illustrated by quoting an instance of realized savings from use of new pavement technologies. For example, the New Jersey Port Authority saved $12.5 million in 1969 by construction of runways at Newark using lime-cement-flyash pavement in lieu of more traditional materials. Other instances could be quoted but suffice it to say that a simplistic analysis made by the FAA in early 1977 and based on an assumed Airport Development Aid Program commitment of $400 million to airport pavements for the year 1985, concluded a construction cost savings for capital items alone of over $240 million for that fiscal year.

SCHEDULES

Overall schedules were provided previously in Figure 3 for various projects. It should be noted from Figure 1, however, that sustaining engineering support to Airport Development Aid Program project needs will continue so long as that program remains in being.

DETAILED ILLUSTRATION OF RESEARCH PROCESS

An explication of the project for validation of nondestructive testing of airport pavement follows. This particular project has been chosen for detailing the research process for two reasons;

(1) intense industry interest because of inherently large achievable cost savings, and

(2) its typical wide-ranging and involved research requirements.

SECTION IV - AIRPORT PAVEMENT EVALUATION USING NONDESTRUCTIVE TESTING

INTRODUCTION

Airport pavements are evaluated for strength characteristics and load carrying capabilities on a periodic basis. The evaluations provide the airport owners with valuable diagnositc information to plan and execute pavement rehabilitation programs, if needed, on a reasonable schedule to prevent major pavement failures that may result in forced closures of the pavement facilities. Such forced closures cause delays and are not permissible for many airports especially those with high numbers of scheduled operations. The program on pavement evaluation using nondestructive testing (NDT) is being pursued by the Federal Aviation Administration (FAA) to provide better diagnostic information from evaluations based on more tests and without disrupting aircraft operations during the testing. In the NDT, vibratory loads are applied and pavement response (deflections) is measured. The test results are analyzed to obtain a pavement modulus and other strength characteristics of the pavements. In addition, the program also includes various designs of rehabilitation pavements and cost/benefit of each design. Inclusion of the cost/benefit aspect in pavement design provides airport operators with some economic rationale for selecting a design and permits them to logically plan for financing the pavement rehabilitation.

PROBLEM DEFINITION

Current FAA standards for pavement evaluation are based on conventional methods relying on test pits (approximately 4 ft. square), static plate load tests and material sampling for laboratory examinations.[1] Figure 1 shows a plate load test being conducted in the test pit. Each test pit requires 2 to 3 days for preparation and field testing, and a facility, such as a runway, must be closed for the work. In general, two or three test pits are used to diagnose the condition of the entire facility. Consequently, there is a low reliability in the assessment of the strength variations, and the confidence in the results is low. The introduction of NDT is expected to overcome many of the disadvantages of the current standard method.

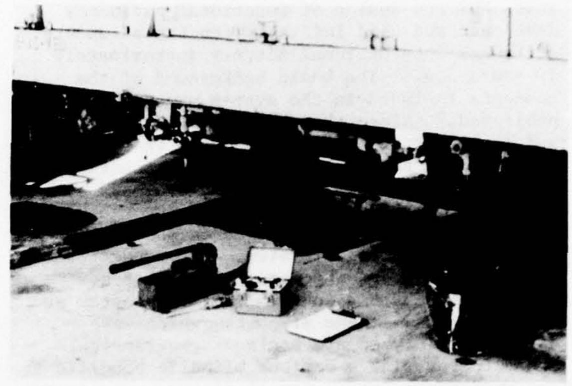

FIGURE 1. Plate load test being conducted through test pit.

BACKGROUND

In 1971, FAA initiated an R&D program on pavements for civil airports. The purpose of the program was to develop design criteria, material requirements, and construction techniques based on existing technology to upgrade the old FAA standards and guides on pavements. Most of the work was contracted to the U. S. Army Waterways Experiment Station (WES), Vicksburg, Mississippi. One of the line items in the program was the development of a pavement evaluation procedure using NDT with the 16-kip vibrator owned and operated by WES. The development was based on the results of correlation between the dynamic stiffness modulus (DSM) values obtained from the dynamic load-deflection curves and the load carrying capacities of numerous pavements determined from conventional methods. A reasonable association was found between the modulus values and capacities.[2] As a result, the FAA issued an advisory circular on the use of NDT devices in evaluating airport pavements.[3]

In 1973, FAA initiated a second R&D program with WES on "New Pavement Design Methodology." The program was to develop pavement design and evaluation methods that relied on more advanced theories than the conventional semiempirical methods. These advanced methods were considered to provide a better understanding of the complex mechanism of pavement responses and performances under various wheel loadings, climatic conditions and time. Linear layered elastic, nonlinear elastic and viscoelastic theories appeared attractive for application to pavement design and evaluation. A design method based on linear layered elastic theory was completed for flexible pavements.[4] Development of a comparable method for rigid pavements and associated evaluation procedures for both pavement types are in progress.

Based on the promising results found in an in-house review of pavement design and evaluation methods and the interest expressed by industry, FAA investigated the system using frequency sweep NDT and design of functional pavements developed and used initially for the pavements at Newark International Airport approximately 10 years ago.[5] The basic background of the concepts included in the system was previously published.[6] Since then additional developments and improvements have been made to the system but have not been documented. Consequently, in 1975, Nai Yang, the original developer of the system, was contracted by FAA through WES to document the entire frequency sweep NDT and functional design system. The documentation is completed,[7] and the entire system is now being tested by FAA in a validation program at four airports. These airports, which were selected mainly on the basis of geographical locations providing various climatic conditions, are Burlington International Airport, Burlington, Vt., Stapleton International Airport, Denver, Co., Tampa International Airport, Tampa, Fl., Los Angeles International Airport, Los Angeles, Ca. The frequency sweep NDT and design analyses have been completed for the pavements at the four airports, and the final report is in preparation. Major components of the system include the: (1) vibratory testing of pavements in the frequency sweep mode, (2) determination of the modulus of elasticity from the frequency-response data, (3) determination of the present functional life of pavements up to 5 years based on aircraft pavement interaction, (4) consideration of all possible construction material candidates for design of new and rehabilitation pavements, and (5) determination of the cost/benefit in terms of present cash values for each design scheme.

TECHNICAL APPROACH

Vibrator for NDT

The development of the FAA pavement program dealing with NDT is based on dynamic load-deflection characteristics of the pavement obtained with the 16-kip electrohydraulic vibrator owned and operated by WES. Other NDT equipment, such as Dynaflect, Road Rater, California Deflectometer, Benkelman Beam, and Deflection Device have been used on highway and airport pavements.[8,9] These devices have been designed mainly for testing highway pavements. The Air Force uses a large vibrator to induce compressional, Rayleigh, and shear waves into the pavement to obtain the phase velocities of wave propagation through the various layers of the pavement system.[10] These velocities are used in theoretical relationships to determine the dynamic moduli of elasticity of the pavement layers.[11] Criteria for using a vibrator for NDT of civil airport pavements are found in FAA Advisory Circular 150/5370-13. Figure 2 shows the 16-kip WES vibrator with its three basic parts. In testing, a load plate with 16-kip static load is hydraulically lowered on the pavement, and a dynamic load is superimposed on the static load. The load plate is interchangeable, but for airport pavement testing, an 18-inch diameter plate is generally used. Two modes of vibration are possible: (1) load sweep, and (2) frequency sweep. In the load sweep mode, a frequency is preselected (range is 5 Hz to 100 Hz) and the dynamic load at the preselected frequency is applied up to a maximum of 15 kips.

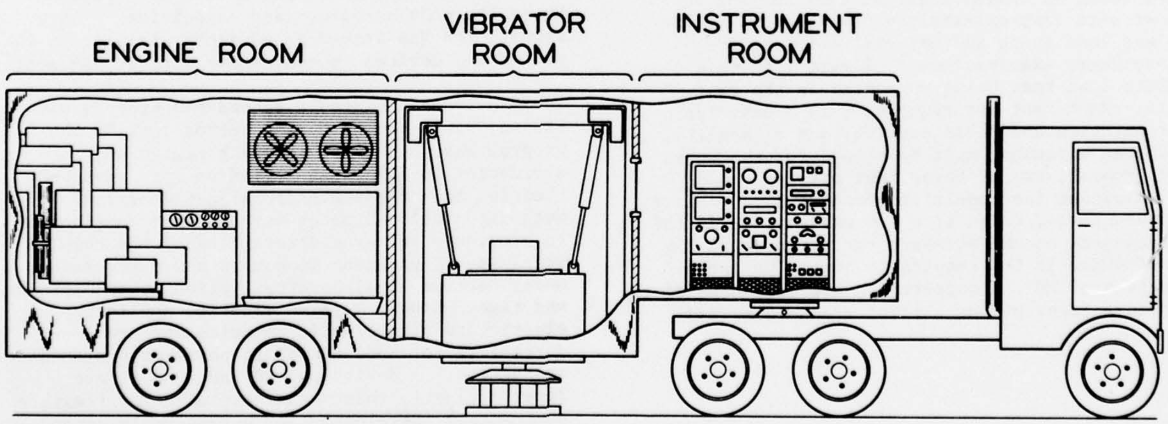

FIGURE 2: Sixteen-kip vibrator used for NDT.

In the frequency sweep mode, a dynamic load is preselected that will give a meaningful measure of pavement response, and the test with the selected dynamic load is conducted at various frequencies, generally from 5 Hz to 60 Hz. For both test modes, the load and deflection are measured only under the dynamic loadings; the dynamic loads are measured with a set of load cells and the deflections are determined by intergration of the velocity-time traces obtained from velocity transducers placed on the load plate and, if desired, at points away from the plate. When necessary, the NDT with the 16-kip vibrator can be accomplished at nighttime to avoid interference with aircraft traffic.

Evaluations Using DSM

Pavement evaluation based on the DSM uses the load sweep mode of NDT at a frequency of 15 Hz. Figure 3 shows a dynamic load-deflection curve obtained from a test which is completed in approximately 2 minutes. The DSM value is the slope of the upper portion of the curve shown in Figure 3. Test procedures, and requirements for the number of test points, analysis of data, and determination of the load-carrying capacity of the tested pavement are detailed in FAA Advisory Circular 150/5370-13 and will not be repeated here.

In the evaluation procedures for the linear layered elastic method, the contractor proposes to use the curve shown in Figure 3 to determine the modulus of elasticity values for the pavement subgrades.[12] These values are then used in the layered elastic analyses to determine the loads on the pavement surfaces that will not cause excessive stresses, strains, and deflections of the pavement layers.

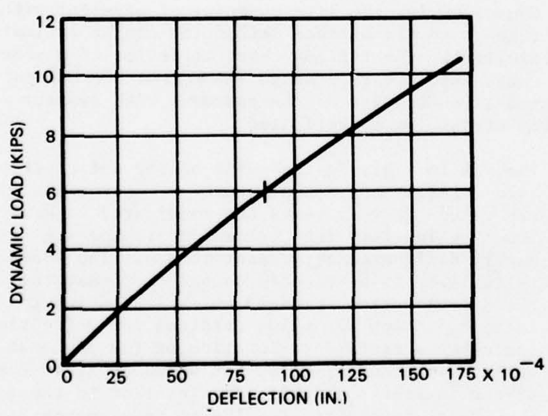

FIGURE 3: Dynamic load-deflection used in DSM methods.

Evaluation Using Frequency Sweep NDT and Design of Functional Pavements

All the theoretical background and the development of the mathematical relationships and procedures in the evaluation using the frequency sweep NDT and in the design of functional pavements are found in references 6 and 7. The entire system is programmed for computer analysis. The following paragraphs discuss the basic test, evaluation, design and analysis procedures without providing the theories and numerous mathematical relationships.

Modulus of Elasticity from Frequency Sweep NDT

The result from the frequency sweep mode of NDT at each test point is a pavement response versus frequency relationship as shown in Figure 4. This test requires 8 minutes at a cost of approximately $40 per test point. A critical point on the curve is the point of maximum deflection which can vary with the type and strength of the pavement. For the curve shown in Figure 4, the maximum deflection is at approximately 9 Hz. This frequency is designated as the resonance under the steady-state vibration. The Figure 4 relationship from the resonance to the maximum frequency is used in the summation portion of the equation shown in Figure 5 for determining the modulus of elasticity (E) of the pavement at the test point. A 200 to 300-ft. spacing of test points along runways and taxiways is recommended for the frequency sweep test. Judgment is used to locate a sufficient number of test points on cross taxiways at entries to parking aprons, along traffic lanes on aprons, and at gate positions to obtain meaningful statistical *variations occurring in the pavement facilities*. Consequently, a 10,000 ft runway facility, for example, may have up to 50 E values that are

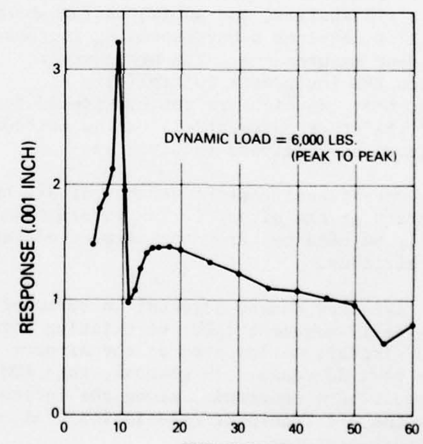

FIGURE 4: Responses from frequency sweep NDT.

$$E = \frac{1}{2a} \cdot \frac{1}{\frac{1}{F} \sum_{1}^{\infty} \frac{Z(U)}{U}}$$

WHERE: F = DYNAMIC LOAD (PEAK-TO-PEAK) (LBS.)

a = RADIUS OF PLATE (IN.)

U = RATIO: FREQUENCY TO RESONANT FREQUENCY

Z(U) = DEFLECTION (IN.) AT U

FIGURE 5: E value determination from frequency response relationship.

considered statistically to obtain a representative pavement E value which is the average E minus one standard deviation. This pavement E value for each facility is representative of the modulus under the test condition which is generally at normal moisture content of the subgrade. The E value is used in further analyses to obtain the subgrade E value at normal moisture content and pavement and subgrade E values at the saturated condition. The set of four pavement E values for each facility becomes an input file to be used in the determination of the present functional life of the existing pavement facility, and in design of new and rehabilitation pavements.

Present Functional Life (PFL)

The present functional life is an estimate of the time in years to pavement failure in terms of roughness and cracking from the present condition. An increasing level of roughness leads to failure in terms of intolerable aircraft rideability, and an increasing amount of cracking requires a corresponding increase in pavement maintenance. The procedure to determine PFL includes a multiplicity of factors, many of which are not considered in many of the other pavement evaluation methods. The factors and analyses required are:

(1) Operational takeoff weights of all types of aircraft at the airport. The information can generally be obtained from the airport operator or the airlines.

(2) Aviation demand forecast in terms of average daily movement (ADM) of existing aircraft and new aircraft anticipated at the airport for the next 20 years. In general, this ADM is a result of a compromise among the forecasts made by the Air Transport Association, FAA, and the airport operator.

(3) Utilization of the airport facility in terms of longitudinal and transverse load distributions on all pavement facilities for landing and takeoff modes of aircraft operation. This utilization constitutes the airport traffic distribution (ATD).

(4) File of pavement E values from NDT.

From the first three factors listed above, aircraft traffic movements are determined for each facility during a given year of operation. Using the operational takeoff weights of aircraft (first factor listed above), touchdown weights at a sinking velocity of 4 ft. per sec. and landing roll weights are determined. For the three operational weights (takeoff, touchdown, landing roll) the radii of tire footprint area and factors for equivalent single wheel loads are calculated. In addition, the longitudinal probability distribution of touchdown points is determined, and for each type of existing pavement, the surface deflections and component stresses under the three operational weights for every aircraft type are determined by the general equivalent layered system (GELS) computer program using the pavement E values obtained from NDT. Considering the stress and deflection levels imposed by the different aircraft, the equivalent operation of a standard aircraft used in design is obtained by the ratio of the number of operations of each aircraft to the number of operations of the standard aircraft. When the ratios are summed over all types of aircraft used at the airport for the three operational weights, the annual number of operations of the standard aircraft is obtained.

The next requirement in the procedure is the determination of the anticipated life capacity of existing pavements subjected to the repeated deflections and stresses imposed by the standard aircraft. In the process, the surface deflection and critical layer stress are determined by GELS, and the pavement's capacity to withstand permanent deformation and stress accumulations is evaluated. The rate of accumulation of permanent deformation is related to the surface deflection and the shape of the deflection basin. Consequently, the life capacity of pavement with respect to the surface deflection can be estimated. Similarly, the fatigue characteristics of pavement components are related to the stress levels, and the life capacity of the pavement with respect to stress can be estimated.

The PFL in years is the ratio of the anticipated life capacity and annual number of operations. PFL values above 5 years are considered to have lower reliability than below 5 years and are merely designated as greater than 5. The lower reliability is attributed to the fact that the PFL determination is based on estimated input factors. A low PFL value obtained for deflection indicates a rapid deterioration of the pavement surface smoothness; a low PFL value obtained for stress indicates a rapid deterioration in the structural integrity, leading to maintenance requirements.

New and Rehabilitation Pavements

The design of functional pavements considers new pavements and rehabilitation pavements such as overlays and keel sections. Types of new pavements included are: (1) asphaltic concrete surface over lime-cement-flyash layers or over asphalt stabilized and aggregate bases, and (2) Portland cement concrete surface over cement treated and selected subbase layers or over rolled lean concrete (econocrete) and selected subbase layers. Overlays for rehabilitation on existing pavements include: (1) asphaltic concrete surface over asphalt stabilized base or over lime-cement-flyash layer, and (2) reinforced portland cement concrete over a 1-inch asphaltic concrete leveling course. Various combinations of the new and overlay types of pavements mentioned are incorporated into the keel and sides of keel sections. A total of 10 different design schemes is provided in the design of functional pavements.

In the design process, the factors and analyses discussed for the determination of PFL are used. The number of operations of the standard aircraft is obtained, and the deflection limit based on acceptable aircraft vibration and stress limit of each layer are set for the design life of the pavements. By an iterative process in the GELS program, the layer thicknesses are obtained. The thicker layer required, either by deflection limit or stress limit, governs the design.

Cost/Benefit Analysis

To permit comparisons of the various designs for new and rehabilitation pavements on a rational basis, a cost/benfit analysis is conducted after determination of the required layer thicknesses. Input to the cost/benefit analysis includes latest available data on bulk unit construction material costs and common and skilled labor costs for the airport or for the region. In addition, financial cost elements are incorporated; these include: (1) annual interest rate of bonds, (2) annual rate of cash discount, (3) rate of annual escalation of construction cost, (4) rate of annual escalation of maintenance need, (5) maturity of revenue bond in years, and (6) effective service life of pavement in years. For each pavement facility, the unit price of component layers in dollars per inch of thickness per square yard is determined and summed for all layers to obtain the initial construction cost (ICC). Then, the annual maintenance cost (AMC) is determined. The AMC is a function of ICC, pavement strength and variance of the strength. Both the ICC and AMC are converted to present cash value (PVC). For a pavement facility with keel section design or varying cross section, a weighted average of the PCV is determined. The final PCV for every facility is presented in tabular form for comparison.

SUMMARY

The FAA is engaged in an extensive R&D program on airport pavement evaluation using NDT. A part of the program has been completed and standards have been issued on the completed work. Additional efforts on validation of the methods involving layered elastic theory and frequency sweep NDT coupled with design of functional pavements are in progress. These efforts are expected to be completed by the end of this year. Results of the R&D program, thus far, indicate that NDT is quick and accurate. (Time required per test is up to a maximum of 8 minutes.) The quick testing with the nighttime testing capability means that NDT will not interrupt aircraft traffic. Cost per test point for NDT is low (approximately $40 up to now). Consequently, the diagnosis can be based on data obtained from many tests (40-50 tests per runway have been used) which permit a good assessment of the pavement strength variability and provide a high confidence in the pavement evaluation results. The advantages of NDT found to date are promising, and it appears that the use of NDT will benefit all those who are involved in airport pavement evaluation and design, particularly if a comprehensive cost/benefit analysis of various pavements for rehabilitation is included in the package.

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WIND SHEAR AND WAKE VORTEX PROGRAM

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BIOGRAPHY

Guice Tinsley is Chief of the Wind Shear and Wake Vortex Branch (ARD-480). He has a BS in Mechanical Engineering from Purdue University and received a MS in Business Administration from The George Washington University in 1968. He has a Commercial Pilot rating and has flown a variety of military aircraft including a tour as a test pilot in the C-141 program at Edwards Air Force Base, California and F-4, Phantoms in Vietnam. Prior position with the FAA was Chief of the Terminal Navigation Branch with responsibility for CAT III ILS Development, All-Weather Landing Program and Airport Lighting.

FRANK G. COONS, Jr.
Associate Program Manager for Ground Systems and Forecasting Development

Mr. Coons is the associate program manager for ground systems and forecasting development in the FAA's Wind Shear Research and Development Program. He has been on the wind shear staff since its inception in August 1975. Prior to joining the Wind Shear Program, Mr. Coons worked for the FAA's Aviation Weather Systems Branch as project manager in fog dispersal systems evaluation and systems engineering studies of weather support for the Upgraded 3rd Generation Air Traffic Control System. Prior to joining the FAA in 1970, he worked as an Advanced Weather Officer in Headquarters Air Weather Service on a variety of weather related research and development projects. Mr. Coons has 3,800 hours of flying in weather reconnassiance aircraft. He graduated from Millersville State College, Pennsylvania in 1954 with a Bachelor of Science in Education. He received his basic meteorological training at the University of California at Los Angeles and his advanced training at Pennsylvania State University in 1964 and 1965.

LT COLONEL LARRY WOOD
Associate Program Manager for Airborne Systems

Colonel Wood is a member of the United States Air Force with an assignment to the FAA. He holds a BS and Masters Degree from the Air Force Institute of Technology in Electrical Engineering. He is a Command Pilot with experience in F-100's, B-52's, B-47's, and completed a Vietnam tour in 0-1's. Colonel Wood was awarded the Distinguished Flying Cross and 18 Air Medals for his extremely hazardous flying activities as a Forward Air Controller. His present position in the FAA is the management of all airborne system developments relative to wind shear.

MYRON E. CLARK
Associate Program Manager for Wake Vortex

Mr. Clark is the associate program manager for Wake Vortex in FAA's Systems Research and Development Service. He has been a member of the Wind Shear program staff since its inception in August 1975. Prior to joining FAA he served as a Lt. Colonel in the U.S. Air Force and holds a Master Navigator's rating, accruing 6,100 flight hours in multi-engine jet and reciprocating aircraft. Mr. Clark is a University of Maryland graduate with a Bachelor of Science in Business Management.

ABSTRACT

The Federal Aviation Administration's Wind Shear Program has developed three potential near-term solutions to the aviation problems created by hazardous low-level wind shear. They include: development of a ground-based Low Level Wind Shear Alert System to detect shear in the terminal area, development of a Hazardous Wind Shear Advisory Service in cooperation with the National Weather Service to alert pilots when strong wind shear conditions are going to affect airport operations and development of avionic displays to assist pilots in coping with shear during approach and landing. Each of the above potential solutions is reviewed in this paper.

The Federal Aviation Administration's Wake Vortex Program has sponsored the design, development, and testing of a Vortex Advisory System (VAS) by the Transportation Systems Center. This system has been installed at Chicago's O'Hare Airport for operational implementation.

BACKGROUND - Wind Shear

Since July of 1973 there have been seven U.S. air carrier accidents attributed to encounters with strong low-level wind shear (as determined by the National Transportation Safety Board)[1]. Within the past 24 months the efforts of Federal Aviation Administration (FAA's) Wind Shear Engineering and Development Program has developed potential near term solutions to the low-level wind shear problem in three separate, but related, development areas. The purpose of this paper is to briefly review those solutions to the wind shear problem which could be implemented by 1979.

In constructing the FAA's Wind Shear Development Plan it was evident that no single area of investigation within the three major areas of the plan would provide a total solution.[2] Therefore all three development areas have been pursued simultaneously. Those three major areas are: (1) develop a ground-based system capable of detecting strong wind shear conditions in major airport terminal areas, (2) provide a Hazardous Wind Shear Advisory Service for terminal operations based upon forecasts provided by the National Service (NWS) and (3) provide an on-board indication of wind shear conditions to pilots for safe approach and landings. Potential solutions have been developed for all three major program areas and they are currently being evaluated. Brief reviews of each solution are offered below.

GROUND-BASED WIND SHEAR DETECTION

In all the accident cases mentioned above, substantial differences existed between the surface winds reported for aircraft operations and the winds actually encountered by the accident aircraft. Normally, airport winds are measured in the runway complex as near as possible to the average aircraft lift-off position on the main runways. At larger airports this could be miles from the active approach zone being used at the time. For example, at Chicago's O'Hare Airport the centerfield anemometer, or operating wind sensor, is located approximately 2 nautical miles (3.7 km) from the ILS* middle marker of the approach to runway 14 Left. When thunderstorms begin to impinge on the airport operating corridors, airport wind conditions can change dramatically over short distances and times. Winds measured at one point only, in most cases, will be much different than those encountered by aircraft operating in and out of the airport. This was dramatically illustrated by both the Eastern 66 accident at JFK which occurred on June 24, 1975[3] and the Continental accident at Denver which occurred on August 7, 1975.[4]

Low Level Wind Shear Alert System

A precursor of strong to severe low level wind shear is a wind shift zone known as the thunderstorm gust front. The detection and movement of that zone is therefore important to safe airport operations. Over the past several years, the FAA has evaluated a number of ground-based wind shear sensor systems designed to detect hazardous wind shear in the terminal area. Of those designed to detect shear associated with thunderstorm outflows (and in particular the gust front), the Low-Level Wind Shear Alert System (LLWSAS) has been chosen for installation at 60 U.S. airports. The 60 airports were chosen on the basis of an FAA in-house benefit/cost study. The analysis weighed the cost of procuring, installing and operating the LLWSAS over a 20-year period versus the cost of wind shear related air carrier accidents over the past 7 years ($88.5 million) and the potential of having another major accident due to low-level shear from thunderstorm. Sixty airports were judged to be cost beneficially for equipping with the LLWSAS.

The LLWSAS system consists of up to six additional anemometers nominally sited in the airport approach and departure corridors at from 3,000 (914m) to 4,000 (1.2km) feet from the runway thresholds. The wind sensors are mounted on wooden poles at altitudes that range from 20 (6m) to 50 (15m) feet depending upon the surrounding terrain and wind flow obstructions. At airports where the runway layouts do not lend themselves to 360 degree coverage, the sensors are located as before but also in the quadrants from which the maximum number of thunderstorms cross the airport.

* Instrument Landing System

Data are taken at each remote anemometer site and VHF* (162-170 MHz** band) radio linked back to the airfield control tower where they are compared with the centerfield or operating winds. A mini computer, installed in the control tower equipment room, performs the systems computations, command functions and drives system displays available to air traffic controllers. When the vector difference between any one or more remote sensors and the centerfield sensor exceeds 15 knots (7.7 mps), the controller's displays provide readings from the affected site(s) in addition to the centerfield winds. The 15 knot vector difference was selected as the wind shear alarm trigger point based on a suggestion from Dr. Edwin Kessler, Director of the National Severe Storms Laboratory and Dr. Gordon Little, Director of the Wave Propagation Laboratory. Because of the extensive study and analysis by the Laboratories of numerous gust fronts, they believed the 15 knot vector difference to be the appropriate value. Those readings are relayed to pilots arriving or departing the airport through the air traffic control voice frequencies. The LLWSAS accurately and reliably measures the low level horizontal shear. Providing the pilot with this information would eliminate departures into a known hazard such as the Denver accident or approaches into severe gust front areas such as the JFK and Philadelphia accidents.[5] A concept of the LLWSAS is provided in Figure 1.

* VHF = Very High Frequency
** MHz = Megahertz

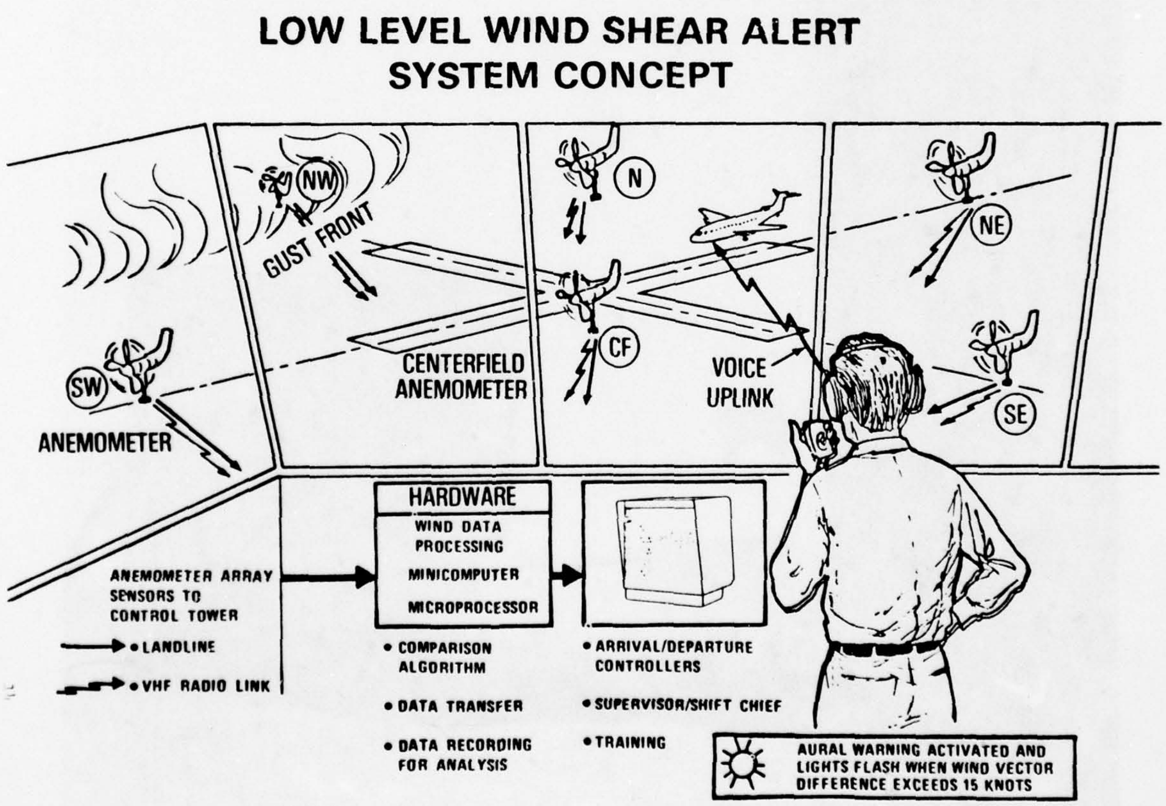

FIGURE 1. Low Level Wind Shear Alert System Concept

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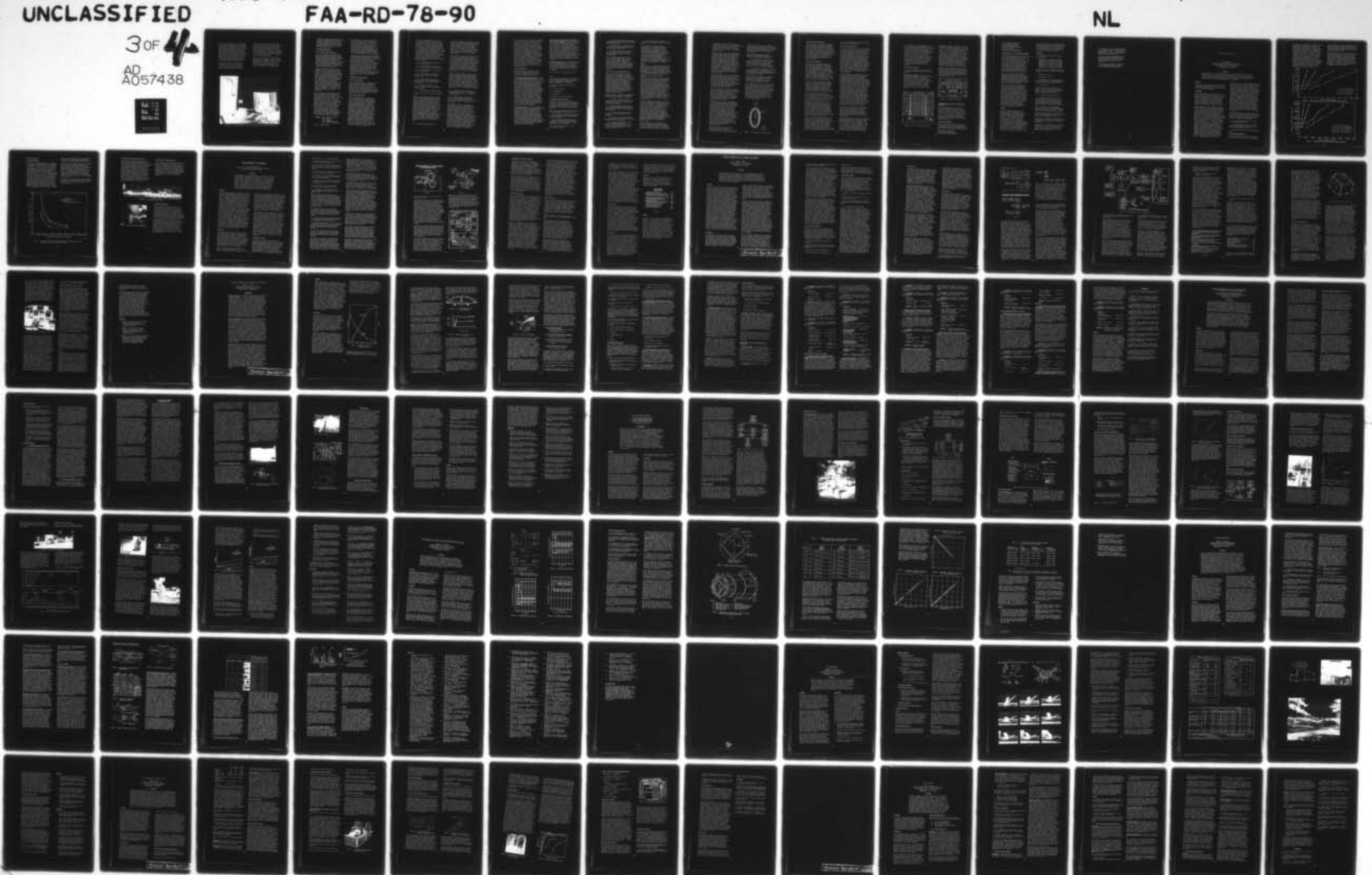

Wind data at each remote site are averaged for 30 seconds through an electronic filter and each site is sampled every 10 seconds by the radio link. Winds from the centerfield anemometer are continuously averaged over 2 minutes with any gust exceeding a 9-knot threshold within the past 10 seconds also being displayed. All anemometers currently used in the system are Belfort Instrument Vector Vanes. The mini computer is a Digital Equipment Corporation PFP-1103 having a 4096 word random-access-memory, real time clock input, priority interrupt control logic and an automatic restart feature.

The LLWSAS is capable of driving up to ten displays but most control towers at the candidate airports will require only two. The displays are readable in bright sunlight and currently consist of numeric, seven segment, incandesent digits configured in up to six rows. The top row of the display is always the centerfield wind direction, speed, and gust reading. Rows below the top relate to remote anemometer locations by general direction, i.e., north (N), northwest (NW), etc. The light intensity for each display line is manually controllable as is an audio alarm. Figure 2 is a photograph of the LLWSAS display.

Evaluation of the system is still being conducted at Denver, Houston, Oklahoma, Atlanta, Tampa and John F. Kennedy airports. Boston, Logan Airport is scheduled to receive the next LLWSAS in the summer of 1978. The LLWSAS is scheduled to be installed at 20 more major airports by the summer of 1979.

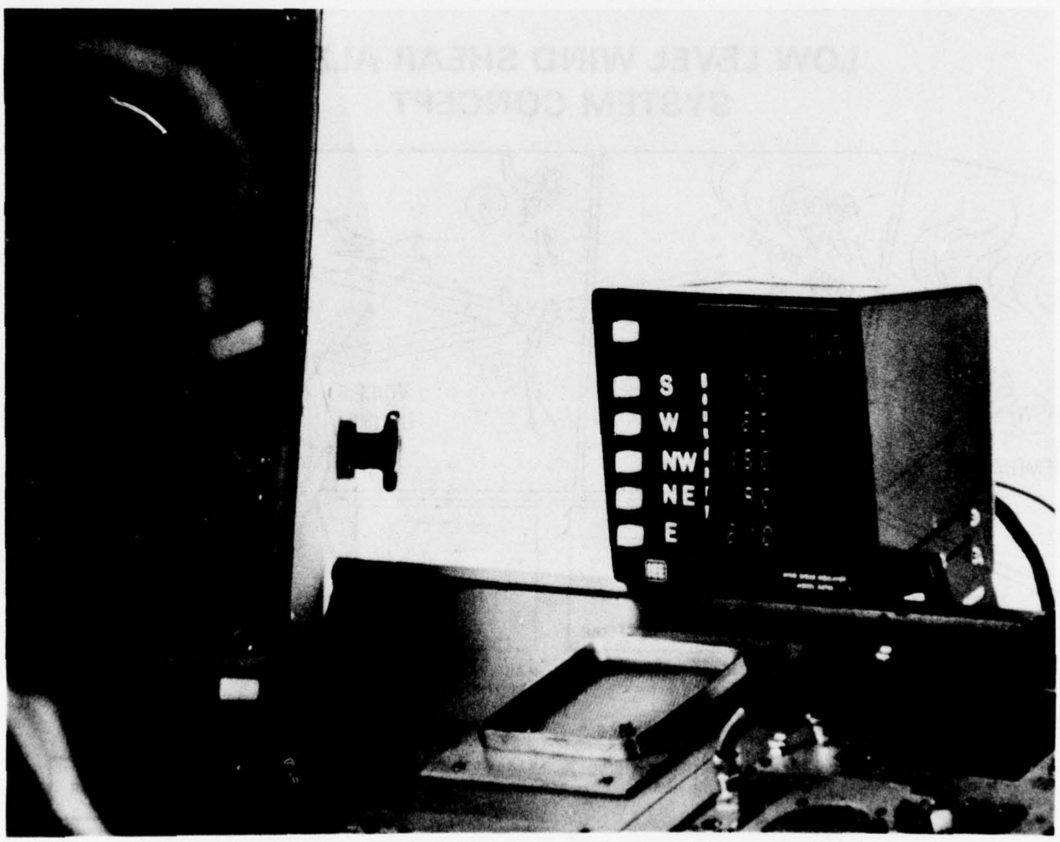

FIGURE 2. Low Level Wind Shear Alert System Air Traffic Control Tower Display

In addition, feasibility studies are being conducted to determine the effectiveness of lasers to measure winds under low visibility conditions and for clear air wind measurement using radar.[6] Plans are underway to develop a prototype of the most promising technique.

WIND SHEAR FORECASTING

Low Level Wind Shear Forecasting

Early in the manned simulation program conducted in the DC-10 at Douglas, wind shear advisories were passed to the pilot. Advanced notice of an impending shear was valuable information for the pilot to determine his approach strategy. If shear could be forecast with reasonable degree of skill, some benefit could be gained by passing this information to aircrews prior to landing and takeoff operations.

During the winter of 1976-77, the FAA sponsored the National Weather Service to conduct a test of a Wind Shear Advisory Service for pilots using seven east coast airports. The test airports were grouped around three cities, New York (JFK, LGA and EWR)*, Philadelphia and Washington, D.C. (DCA and IAD)*. Forecasts of strong low-level wind shear in the surface to 1,500-foot level within a 5 n.mi.** (10km) radius of the subject airports were passed from the NWS Forecast Offices that are responsible for those cities to the FAA's Air Traffic Control Systems Command Center in Washington, D.C. They were subsequently relayed by telephone to the airports affected in the form of advisories.

For the purposes of these tests, strong shear was either a vector difference of greater than 15 knots (7.7 mps) in the horizontal or greater than 5 knots (4.6 mps) per hundred feet in the vertical. The advisories were of the 2-3 hour variety with a lead time of 1 hour. The advisory bulletins would contain wind direction and speed for conditions on both sides of frontal zones, the time these conditions would affect the airport and the cause of the shear, i.e., cold front, warm front or low-level jet. The pilots received the advisories primarily from the Automatic Terminal Information Service (ATIS) which is a transcribed message all pilots using the airport are requested to access prior to take-off or landing.

* Airports: JFK = John F. Kennedy
EWR = Newark
LGA = LaGuardia
DCA = Washington National
IAD = Dulles International

** n.mi. = nautical miles

The techniques used to forecast low-level wind shear events are quite detailed and will not be reviewed here. A detailed report on the test, with results and recommendations for improving the advisory service, will be published in an FAA technical report this coming summer. However, sufficient success was demonstrated during the tests that the NWS has agreed to explore the implementation of a nationwide wind shear advisory service during 1978.

Forecast procedures and advisory dissemination techniques are being developed now. Within the near future, low-level wind shear forecasts and/or advisories will become part of a Hazardous Weather Advisory Service in which all types of weather related hazards to aviation will be forecast over 1-2 hour time periods by NWS. Advisories to pilots concerning the hazards will be given the highest priority for dissemination by FAA commensurate with safe operating procedures. Communication techniques such as: transcribed broadcasts, voice response systems and data link are currently being evaluated as potential hazardous weather advisory vehicles.

AIRBORNE WIND SHEAR SYSTEMS

Nature of the Problem

The basic requirement of an airborne wind shear system is to detect the condition and inform the pilot of the severity. A decision can then be made to continue the approach or make a missed approach. If the approach is continued, the pilot requires guidance in the form of information displayed in the cockpit for controlling the aircraft through the shear condition.

Manned Flight Simulation

To aid in the selection of suitable wind shear related avionics, it was necessary to identify the various functions which an airborne wind shear detection/information system could fulfill and to evaluate the most promising approaches. A series of manned flight simulation experiments was conducted to identify and refine the most effective pilot - aiding concepts. The experiments were grouped into three phases of simulations using both training and engineering development simulators and modelling short-haul, medium-haul and wide-body jet transport aircraft in current airline operations. The simulators were all equipped with six-degrees-of-freedom movement, visual systems with variable weather and visibility, and a full complement of controls for all flight crew positions. Each was capable of simulating all flight guidance and control modes available on the aircraft in service use.

Phase I of the simulation effort was a controlled screening of candidate systems and techniques.[7] The most effective were selected for in-depth analysis and further refinement. The bulk of these experiments were conducted in a DC-10 training simulator at the Douglas Aircraft Company Flight Crew Training Center in Long Beach, California. In this phase of the simulation effort, pilot performance data and subjective pilot opinions were recorded on highly experienced pilots most of whom held DC-10 pilot qualifications. The pilots were subjected to various flight scenarios and wind shear conditions while being aided by the following discrete concepts:

(1) Wind Shear Advisories based on ground-based sensor data;

(2) Panel display of groundspeed versus vertical speed for a 3° glide slope;

(3) Panel display of wind speed and direction (from INS):*

(4) Panel display of groundspeed integrated with conventional airspeed indicator (ΔV);

(5) Panel and simulated head-up display of difference between along-track wind component at surface and aircraft altitude (ΔW);

(6) Panel and simulated head-up display of flight path angle and potential flight path angle;

(7) Panel display of angle-of-attack; and

(8) Panel display of rate-of-airspeed change.

The results of those experiments indicated that groundspeed/airspeed comparison (ΔV) ranked as the best aiding concept by pilot opinions and by the comparison of recorded landing performance.[8] The second best aiding concept was found to be the along-track wind component comparison (ΔW), either head-up or head-down, but particularly when presented on a head-up display. There was also an indication that the head-up displayed flight path angle has some merit. As a continuation of Phase I, the top ranking aiding concepts were reexamined in the Flight Simulator for Advanced Aircraft (FSAA) at NASA/Ames Research Center using a Boeing 737 model. The results of that simulator experiment verified the findings from the previous Phase I simulation efforts.

* INS - Inertial Navigation System

The Phase II Simulation experiments were conducted in the Moving Base Development Flight Simulator (MBDFS) at the Douglas Aircraft Company facility using the DC-10 model. These experiments provided an in-depth evaluation of improved ΔV, ΔW and flight angle (both air and ground derived) displays. This activity also evaluated a modified flight director system (MFD) developed by Collins Radio.

The results of the more detailed evaluations in the Phase II simulations confirmed that the groundspeed/airspeed comparison (ΔV) provides significant aid to the pilot and the along-track wind component comparison (ΔW) provides some aid to the pilot in detecting and coping with wind shear.[9] In addition, it was also shown that the modified control laws (algorithms) for flight director/thrust commands also significantly increased the pilots ability to handle wind shear encounters. Pilot acceptance of each of these concepts was high.

Phase III flight simulation experiments were conducted at both the NASA, FSAA, using a Boeing 727 model, and at the Douglas MBDFS, using a DC-10 model. The purpose of this series of experiments was to evaluate several different methods of displaying the ΔV concept in the cockpit, to optimize the MFD control laws/algorithms for wind shear and to investigate the potential of two concepts to aid the pilot in making the missed approach or go-around decision. The go-around aids evaluated were:

(1) Panel display of energy rate (a comparison between actual total energy rate of change and desired rate of change for a 3° glide slope).

(2) Panel display of acceleration margin (a comparison between aircraft acceleration capability and the acceleration that will be required to overcome the shear (ΔA)).

The Phase III simulation results again demonstrated that the ΔV and MFD concepts were effective in providing the pilot the information required to successfully negotiate hazardous wind shear conditions. The ΔV concept was successful in all the methods in which is was presented: groundspeed displayed on a digital readout; groundspeed displayed as a second needle on a conventional airspeed indicator (round dial); airspeed and groundspeed integrated into a special velocity indicator (vertical scale); or airspeed/groundspeed command displayed on the fast-slow indicator. In addition, it was shown that the ΔA concept provided timely go-around information for those severe shears that approached or exceeded the performance capability of the aircraft.

The energy rate concept was shown to provide some aid to the pilot in making a go-around decision, but suffered from one serious drawback which is common to several of the unsuccessful concepts (such as angle-of-attack, airspeed rate of change, and flight path angle) which were tested in the earlier simulations. Although all of these concepts provide a positive indication of a shear condition and the severity thereof, the indication is not presented until the shear environment is encountered. In order words, the pilot is given an indication that he has entered a hazardous condition that he did not want to enter. On the other hand, those successful concepts which use groundspeed were shown to be predictive in nature in that they provide an indication to the pilot of the shear condition which lies ahead of the aircraft so that the pilot may take timely action.

Systems Descriptions

A brief description is in order to those systems which were demonstrated to be successful in aiding the pilot to detect and cope with hazardous wind shear:

Airspeed/Groundspeed Comparison (ΔV). - The basic concept which has proven most successful in manned simulation experiments for a wide range of shear conditions on approach is the groundspeed/airspeed comparison. Basically, it is a simple procedure whereby the pilot computes a minimum desired groundspeed by subtracting the headwind component of the runway wind from the approach true airspeed. He then flys a normal approach using indicated airspeed, except that he does not allow the groundspeed to fall below the predetermined value. The procedure automatically causes the pilot to add additional airspeed to compensate for any airspeed loss that will occur when the shear condition is reached. It therefore acts as a predictive procedure so that if the amount of correction needed exceeds the known performance capability of the aircraft, the pilot is given the indication to perform a missed approach prior to penetrating the shear conditions.

Wind Difference (ΔW). - This is basically the same procedure as the groundspeed/airspeed comparison except that the information is presented in a slightly different manner. Groundpseed is used to compute the wind component at the aircraft position and is compared with the wind in the landing area. The wind difference (the difference between the longitudinal components of the inflight wind and the ground wind) is presented to the pilot and represents the amount of shear which the aircraft is approaching and therefore the amount of airspeed that must be added before the shear is penetrated.

Modified Control Laws/Algorithms for Flight Director/Thrust Commands. - In addition to the above systems, modifications were developed for the control laws and algorithms which drive the flight director and thrust commands for control of the aircraft during approach. Modern systems are highly damped for passenger comfort and are not responsive enough for highly dynamic shear conditions. By providing the pilot with a selectable second set of control laws/algorithms which are quicker, more active, and based upon inputs derived from groundspeed, acceleration augmentation and tighter coupling to the glidepath, the ability to traverse wind shear conditions is greatly increased.

Acceleration Margin (ΔA). - Acceleration margin is a measure of the difference between the acceleration capability of the aircraft and the acceleration that will be required to overcome the airspeed change which will occur if the shear is entered. It is calculated as follows:

$$\Delta A = Aa - [Ws - (Va - Vg)] \frac{\dot{H}}{H} \quad \text{(Kts/Sec)*}$$

where:

Aa = acceleration capability of the aircraft computed from known performance data based on altitude, temperature, gross weight and approach configuration. (Kts/Sec)

Ws = Headwind component of runway surface wind (Kts).

Va = True airspeed (Kts)

Vg = Groundspeed (Kts)

H = Altitude (Ft)

$\dot{H}$ = Altitude rate of change (Ft/Sec).

Groundspeed Sensor Development

It should be noted that to implement any of the above successful systems, an accurate and timely groundspeed signal must be provided to the cockpit. Groundspeed bias errors must not exceed $\pm$ 2 knots with a 3 second update rate.[10]

Several methods for providing this information are being developed. The options are:

(1) Inertial Navigation Systems (INS). - For those aircraft so equipped, groundspeed is readily available.

(2) Instrument Landing System (ILS). - A groundspeed sensor which applies Doppler techniques to the RF** carrier or an audio subcarrier of the ILS localizer.

* Kts = Knots, Sec = Second, Ft = Feet
** RF = Radio Frequency

(3) Distance Measuring Equipment (DME) - Equipment/modifications designed to optimize the range rate output.

(4) Weather Radar - Groundspeed is determined by tracking a specially designed radar reflector on the ground.

(5) Radar Altimeter - A system which phase correlates the reflected radar altimeter signals received by two along-track antennas.

INS is already an operational system. The ILS, DME and radar altimeter systems exist in the prototype stage and are awaiting flight testing. The weather radar system is under development. The fabrication and testing of several different types of equipment will allow development of the least costly methods for providing accurate and timely groundspeed to the cockpit.

Additional Airborne Systems Evaluation

Before any devised wind shear detection systems can be recommended for general applications to the aviation industry, their performance and characteristics must be validated in actual flight tests. Following tests in a simulated environment, both the groundspeed sensor and wind shear display systems will be installed in an aircraft and adequately instrumented for follow-on flight tests. As airborne techniques and equipments are refined, flight tests will be conducted to determine specific performance requirements and capabilities that are necessary for airborne wind shear systems.

A Phase IV series of manned flight simulation experiments is also planned. The purpose of this follow-on effort is as follows:

(1) Develop an optimum display or indicator for ΔA and ΔV. This may entail integration of these functions into the modified flight director.

(2) Develop modified flight director control laws/algorithms for use during wind shear conditions encountered during take-off and climb-out.

(3) Evaluate the successful aiding concepts for use during non-precision approaches.

(4) Evaluate the successful aiding concepts for use during day-to-day operations when wind shear is not present.

(5) Evaluate the successful aiding concepts under actual operational conditions (altitude and airspeed restrictions, gear and flap limitations, engine failure procedures, etc.).

(6) Evaluate additional systems developed by organizations outside the government.

The combination of manned simulations, groundspeed sensor development and in-flight testing will allow the selection, identification and description of those systems/procedures/equipments which can be used aboard an aircraft by the flight crew to detect and cope with wind shear. Such an all inclusive program should allow complete performance specifications to be written for the development of airborne equipment, permit detailed operational procedures to be recommended, and assure that the selected systems are cost effective.

SUMMARY

Three solutions to the wind shear problem have been reviewed. It appears that all three are required to reduce the hazard low-level wind shear presents to safe air operations in the terminal area. The FAA will continue to pursue work in each area until the hazard is substantially reduced and essentially eliminated.

BACKGROUND - Vortex Advisory System

A major problem facing our air transportation system is the restricted operating capacity at major U.S. air terminals, with the resulting aircraft delays, when these airports operate near their saturation point. The need to increase airport landing and takeoff capacity, under all weather conditions, without degrading current high levels of aviation safety is of prime importance to the air transportation system. Existing airport and airway system utilization is projected to increase significantly in the future.[11] Potential capacity relief through construction of more air terminals or additional runways at existing terminals is unlikely in the current and near future economic and environmental climate.

A serious impediment to solving our capacity problem is the potential hazards posed by the aircraft vortex effort. An aircraft in flight leaves in its wake two counter-rotating cylindrical air masses trailing aft from the wing, termed trailing wake vortices. The characteristics of the wake vortex are established initially by factors related to aircraft gross weight, airspeed, flight configurations, and wingspan. Subsequently, the vortex characteristics are altered and eventually dominated by interactions between the vortices and the ambient atmosphere. Wind, wind shear, turbulence, and atmospheric stability affect the motion and demise of the vortices.[12]

With the introduction of wide-bodied jet aircraft, coupled with the increasing number of total operations, the wake vortex problem has taken on added significance. The vortices from large aircraft can present a severe hazard

to following aircraft which inadvertently encounter the vortices; i.e., the encountering aircraft can be subjected to excessive rolling moments which exceed roll control authority, a loss of altitude, or possible structural stress.

Landing aircraft, before 1970, maintained a minimum of 3 nautical-mile separation under Instrument Flight Rules (IFR) conditions. In March 1970 the separation standards behind the heavy jets (a heavy jet has a maximum certificated take-off weight in excess of 300,000 pounds) was increased by the Federal Aviation Administration to 4 nautical-miles for a following heavy aircraft and to 5 nautical-miles for a following non-heavy aircraft. In November 1975 the standards were further revised by requiring the addition of an extra nautical mile separation for following aircraft with a maximum certificated take-off weight less than 12,500 pounds.

As the percentage of heavies in the aircraft mix increases, the loss of airport capacity increases. At the eight major airports that have been subjects of special Task Force efforts it was found that the capacity loss due to the increasing number of heavy aircraft varies with location and meteorological conditions and may be expected to be as much as 17% if present day separation standards cannot be reduced.[13]

Thus, in the absence of an operational means to locate and track wake vortices, aircraft safety is currently maintained by increasing separations between aircraft pairs to a distance which previous experience has proven is operationally safe. The requirement for increased interarrival separation is diametrically opposed to the goal of increasing airport capacity.

Fundamental to the successful development of a wake vortex advisory/avoidance system is a basic knowledge of the vortex phenomena. Understanding of the physics of vortex generation, the vortex roll-up process, vortex structure, vortex transport, and vortex decay was required to facilitate basic systems development, particularly in the approach airspace environment (ground effect). To adequately document vortex behavior in the operational environment and to investigate the transport, strength, and decay of aircraft wake vortices; four test sites (Denver Stapleton, New York John F. Kennedy, London Heathrow, and Chicago O'Hare) were instrumented to track vortices shed by landing aircraft and one site (Toronto International) for departing aircraft.

The approach zone in the middle marker region was monitored as this is potentially the most hazardous vortex region since all aircraft must pass through the same airspace to execute a landing. The takeoff zone is being monitored to determine if departure procedures applicable to aircraft departing behind heavy aircraft are unduly restrictive because of wake turbulence considerations.

The concept of wake vortex avoidance is based on two considerations which the available wake turbulence data supports:

(1) Meteorological conditions exist a large percentage of the time which cause vortices to move quickly off the flight path or decay rapidly in the approach corridor such as to not present a hazard to aircraft following on the same flight path.

(2) The duration, intensity, and movement of vortices can be reliably predicted if adequate knowledge of the existing meteorological conditions and the generating aircraft's characteristics are known.

The feasibility of developing an applicable vortex system which would use the above considerations is predicated on the observation that separation criteria are overly conservative most of the time.

Over 50,000 vortex tracks have been entered into the data base at TSC. These tracks have been analyzed and the results of this analysis has led directly to the development of the Vortex Advisory System. This analysis indicated that a wind rose criterion could be used to determine when interarrival separations could be uniformly set at three nautical miles for all aircraft types. This wind rose algorithm (Figure 3) which is elliptically shaped is the key to the Vortex Advisory System.[14]

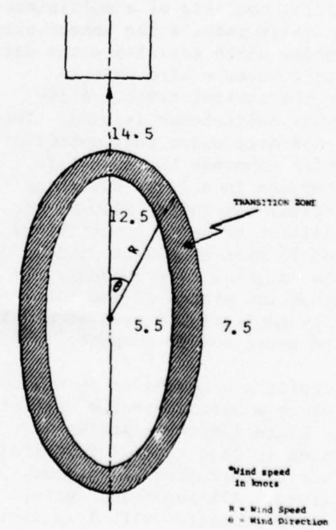

FIGURE 3. VAS Algorithm: Wind Criterion

VORTEX ADVISORY SYSTEM DESIGN

The VAS consists of four major subsystems: a meteorological subsystem for the measurement of the winds; a data-processing subsystem for the processing of the wind data and, using the VAS algorithm, for determining when spacings between inter-arrival aircraft may be reduced; a data-display subsystem for the display of separation requirements and wind conditions to the air traffic controllers; and a performance-monitoring and data-recording subsystem for maintenance and archival purposes.

Meteorological Subsystem

The meteorological subsystem consists of a network of instrumented towers placed about the airport perimeter. In concept, each runway end would have a single 50-foot tower approximately halfway between the runway threshold and the middle marker and about 1000 feet to one side (to prevent vortex impingement on the tower distributing the meteorological measurements). The proximity of runway thresholds, however, generally permits the placement of a single tower to serve two (or more) runways. Seven towers are used in the O'Hare system.

Each 50-foot tower is instrumented with three sets of wind magnitude and direction sensors, one sensor at the 50-foot height and the remaining two at 47 feet. This redundancy provided by a triple-sensor installation greatly increases system reliability, insuring acquisition of valid wind data and detection of sensor failures.

The instrumentation transmitting the meteorological data from each tower to a central facility consists of a multiplexer which sequentially samples the sensor outputs and a line modem which serializes the data and transmits it over a wire pair to receivers in the control tower. A 16-channel, 12-bit multiplexer is used. The multiplexer operates under the control of the modem which commands the scan rate. The modem operates in a lines-switching mode at a crystal-controller 5440-Hz bit rate. In addition to the six multiplexer channels used to read the three wind speed and direction outputs, four channels are used to monitor the status of the tower electronics by monitoring a precision voltage reference and power supply outputs.

Tower electronics are housed in an environmental enclosure mounted near the base of each tower. Since lightning strikes are a major problem in this type of installation, extra care was taken to insure against lightning damage. All input and output signal lines are protected with transient arrestors. The input 60-Hz power line is regulated and contains a separate transient arrestor. Standard FAA control lines are used to transmit the data from each meteorological tower to the control tower.

Data-Processing Subsystem

The serial data stream from each meteorological tower is received by a modem which converts the input into parallel 16-bit words, representing the output of each channel sampled by the tower instrumentation. The output from each receiving modem is input to a microprocessor (one for each meteorological tower). The microprocessors sample the wind data at a 2-samples/second rate. The sampled wind magnitude (R_i) and wind direction (Θ_i) are used to compute a one-minute running average ($\overline{R}$ and $\overline{\Theta}$) by the following scheme: for each sample compute $U_i = R_i \sin\Theta_i$ and $V_i = R_i \cos\Theta_i$; then compute $\overline{U}$ and $\overline{V}$ using a running 128-sample average and compute $\overline{R} = (\overline{U}^2 + \overline{V}^2)^{1/2}$ and $\overline{\Theta} = \tan^{-1}(\overline{V}/\overline{U})$. A one minute average (acutally a 64-second average) was chosen, as the average life of a vortex was found to be one minute.

The microprocessor also performs the functions of failure detection and gust computation. The sampled R_i and Θ_i from each sensor on a tower are compared at the end of each sampling interval (1/2 second) and must agree to within 3 knots and 20 degrees, respectively. Normally, the 50-foot sensor data are selected; if a 50-foot R_i or Θ_i fails, the microprocessor switches to the 47-foot R_i or Θ_i which is not in the wind shadow of the tower. Failure of at least two R_i's or Θ_i's to agree for eight successive samples causes a tower-failure signal to be generated. The microprocessor calculates the wind-gust magnitude using a sliding 32-second interval. Within each 32-second interval the sampled wind magnitude is averaged using a 4-sample running average. Momentary peaks due to high frequency gusts, which would not affect aircraft operations, are filtered out by the 4-sample running average. Any measured peak must be at least 9 knots above $\overline{R}$ to be considered a gust, and the gust value is the peak value observed during each sliding 32-second interval.

In addition to outputs of $\overline{R}$, $\overline{\Theta}$, and gust (if any), the microprocessor outputs system status words to indicate which specific failure (if any) is detected. Failure indications are displayed on the system-maintenance console thereby providing maintenance personnel with the means to effect rapid repairs.

The microprocessor also contains the VAS wind-criterion algorithm in look-up table form for determining the separation standard: the 3/4/5/6 nautical miles or 3 nautical miles for all aircraft. The VAS algorithm consists of two concentric ellipses (Figure 3). The inner ellipse has major and minor axes of 12.5 and 5.5 knots, respectively; the outer ellipse 14.5 and 7.5 knots, respectively. The major axes are alined in the direction

of the runway. If the averaged wind vector is on or inside the inner ellipse, the 3/4/5/6-nautical mile separations are indicated. The region between the two ellipses serves as a buffer zone to prevent rapid changes between the 3/4/5/6- and the 3-nautical mile separation indications. If the averaged wind vector is on or inside the inner ellipse, the wind must increase so as to reach the outer ellipse before the 3-nautical mile separations are indicated. If the averaged wind vector is on or outside the outer ellipse, the wind must decrease so as to reach the inner ellipse before the 3/4/5/6-nautical mile separations are indicated.

Data-Display Subsystem

Two types of displays are used in the VAS, a system monitor display and a runway monitor display.

System Monitor Display - (Figure 4) - The system monitor display is intended for use by the tower cab and IFR-room supervisors. The display indicates in summary form the winds measured at all the meteorological towers. The primary function of the display is to provide an overview of the wind conditions across the airport enabling the supervisor to select an operating configuration which will maximize traffic flow.

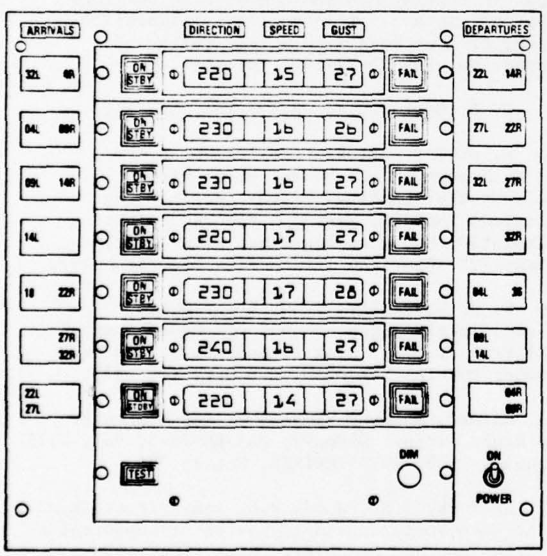

FIGURE 4. The VAS System Monitor Display

Runway Monitor Display - (Figure 5) - The runway monitor display is intended for use by a controller responsible for traffic on a single runway. The controller selects the specific runway via a set of thumbwheel switches. The controller also indicates whether arrival or departure winds are desired; e.g., he/she enters A32L for arrivals on runway 32L and D32L for departures from 32L. The display thereafter accepts data with the corresponding label from the data bus. Thus, if A32L is entered, wind parameters measured at the tower near the approach end of runway 23L are displayed, while a D32L entry causes wind parameters measured at the tower near the approach end of runway 14R to be displayed.

Separations are indicated by a red or green light and are indicated only when an arrival runway is selected. A red light means that 3/4/5/6-nautical mile separations need to be maintained during Instrument Flight Rules; a green light means that all 3-nautical mile separations may be used.

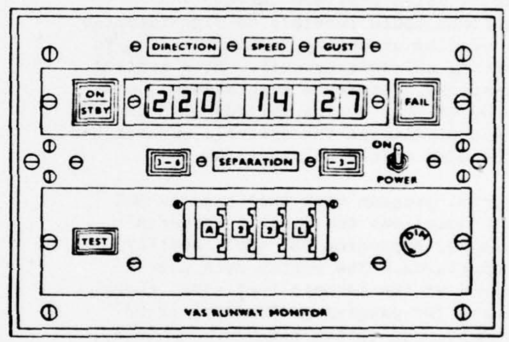

FIGURE 5. Runway Monitor Display

PERFORMANCE-MONITORING AND DATA-RECORDING SUBSYSTEM

To facilitate maintenance of the VAS, a system maintenance panel indicates the status of the various components and whether repairs are needed. All the data output by the VAS are recorded on 9-track digital tape. This tape contains a complete record of all VAS operations for use in system diagnostics and to meet FAA operational requirements for a record of all Air Traffic Control operations.

VAS CANDIDATE AIRPORTS

Based on cost/benefit analyses[15] performed in conjunction with the system development the following airports are considered likely condidates for future Vortex Advisory Systems:

Boston Logan International
San Francisco International
Denver Stapleton International

John F. Kennedy International
Dallas-Fort Worth Regional
Los Angeles International
Atlanta Hartsfield International
New York LaGuardia
Detroit Wayne Metropolitan
Lambert-St. Louis International

APPLICABILITY OF VAS TO DEPARTING AIRCRAFT

The primary consideration in the development of the Vortex Advisory System was it operational application in the arrival mode only. Initial system design did not involve VAS applicability to the take-off situation. Preliminary research assessing the behavior of vortices generated by departing aircraft has indicated that it is feasible to pursue the development of a wind criterion algorithm to be used for establishing departure intervals. This algorithm would be similar to the present VAS algorithm used for arrivals.

Capacity gains realized through VAS operations could possibly be significantly increased by extending VAS separations to departing aircraft as well. Like arrival separations, departure separations would be reduced only during periods when the ambient winds meet the criteria established in the wind criterion algorithm.

The joint program with the Canadian MOT (at Toronto) was the initial research effort for expanding VAS applicability to departures.[16] The vortex data base acquired at the Toronto test site, though adequate for gauging preliminary trend information on vortex behavior and decay, was not extensive enough to statistically derive and validate an algorithm based on the characteristics of the wake vortex generated by departing aircraft. Further data collection efforts will be required to establish the statistical validity of VAS separations for departures and thoroughly analyze all operational safety factors involved in decreasing the current departure standards.

SUMMARY

The Vortex Advisory System offers a reasonable near-term possibility for recovering some of the airport capacity losses attributable to wake vortices. Based on traffic simulation studies; there are no procedural implications which should deter the operational implementation of VAS. The current elliptical wind criterion algorithm used to determine separation requirements appears to be satisfactory for initial operational implementation and evaluation; however, it may prove to be overly conservative. The planned operational demonstration and evaluation of the ORD VAS should be completed by early 1979. Lastly, although most all of the R&D efforts expended toward the development of the Vortex Advisory System have been concerned with the arrival mode, significant recovery of lost capacity may be realized through the utilization of VAS techniques for departure operations.

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CRASH FIRE RESCUE SERVICE

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BIOGRAPHY

John Szymkowicz is a senior program manager of the Airport Safety Branch of the Airport Division, Systems Research and Development Service (SRDS). He received his B.S. degree in Chemical Engineering in 1938; has served as a technical officer in the Air Force for 20 years; and for the last 17 years in the Federal Aviation Administration (FAA) in Flight Standards Service and SRDS.

ABSTRACT

This paper is a brief summary of the R&D effort being conducted by SRDS to meet the current and future requirements for crash-fire-rescue (CFR) services at certified airports.

BACKGROUND

The primary objective of the CFR services is to save lives in the event of an aircraft accident/ incident by providing fire-free exit areas to permit the safe evacuation of passengers and crew. In addition, the CFR services provide a means of preventing the spread of fire by timely intervention and resultant saving of high cost equipment. The latter action has proven to be the greater role of CFR services.

The CFR services at civil airports provide protection for the nearly 200 million passengers who use scheduled and unscheduled air carriers in the U.S. each year. The increase in size of the aircraft has created a burden upon the CFR services in providing the maximum fire protective service at an acceptable cost. The R&D efforts are being directed towards achieving this end. In our review of FAA accidents between 1964 and 1974, there were 2,455 fatalities in this 11-year period of which 395 or 15 percent were attributed to fire. It is noted, however, that twice as many fatal fire accidents occur off airports at distances varying from 0.5 to 18 miles. The effective response of crash trucks is limited to accidents occurring on airports at a distance of 0.5 to 3 miles with response time in 56 percent of the cases were 3 minutes or less. The FAR requirement for aircraft evacuation is 90 seconds and it is important that a rapid response vehicle be available as soon as possible to assure the safety of passengers and crew in the event a fire is hindering their evacuation.

The CFR services are a major expense of an airport operation that cannot be readily associated with a direct service in the operation of an airport. The need for operating the service during operational hours of an airport creates a burden of manning equipment for that period. Presently recommended levels of fire protection presented in AC 150/5210-6B are higher than minimum levels prescribed in FAR Part 139, and it is possible to reduce equipment and extinguishant requirements by selecting the more effective combination for fire extinguishing agents. The need exists for enhanced training program of all CFR personnel in a more proficient manner. There is no standardized course of training for CFR personnel with a majority of CFR training being accomplished as on-the-job-training. Additional problems for hot-fire realistic training is being curtailed because of environmental pollution. This is a real problem and a costly limitation of training.

The basic requirements for CFR are specified in FAR Part 139, and associated advisory circulars. The current R&D effort is directed to the development of regulatory changes and/or advisory circulars. Current projects include:

(1) Testing and evaluation of various firefighting extinguishants.

(2) Developing a concept for a compact, efficient multi-purpose rapid response firefighting agent dispensing system.

(3) Evaluating an aircraft skin penetrator nozzle.

PRODUCTS/EXPECTED BENEFITS

The contribution of CFR services is difficult to assess in that the services rendered cannot

be readily associated with life saved or equipment damage. The high cost of present aircraft indicate the need for CFR services to protect the large investment. The philosophy of operating a service is to be prepared for the worst and to enhance safety programs to prevent fire from starting or in the event it is started to extinguish it before it becomes a raging inferno. The use of improved firefighting agents and techniques will enhance the CFR unit to extinguish fuel fire more rapidly and provide greater protection to passengers and prevent excessive fire damage to aircraft. Use of new type extinguishing agents will require smaller CFR vehicles in lieu of present day behemoths necessary to cover the potential fuel fire of present day large aircraft. (e.g., Figures 1 and 2)

The development of a rapid intervention vehicle (RIV) is considered a great improvement in CFR capability whereby a moderate fire can be extinguished before the large CFR vehicle reaches the scene of the accident.

Another development for CFR use is the aircraft skin penetrator nozzle which would be used in extinguishing fuselage or cargo space fire by flooding the compartment with extinguishing agents. Tests must be conducted to determine most effective extinguishing agent as well as its possible toxicity. This device has the potential of providing an extinguishing agent to suppress fire and also provide a survivable atmosphere for passengers and crew.

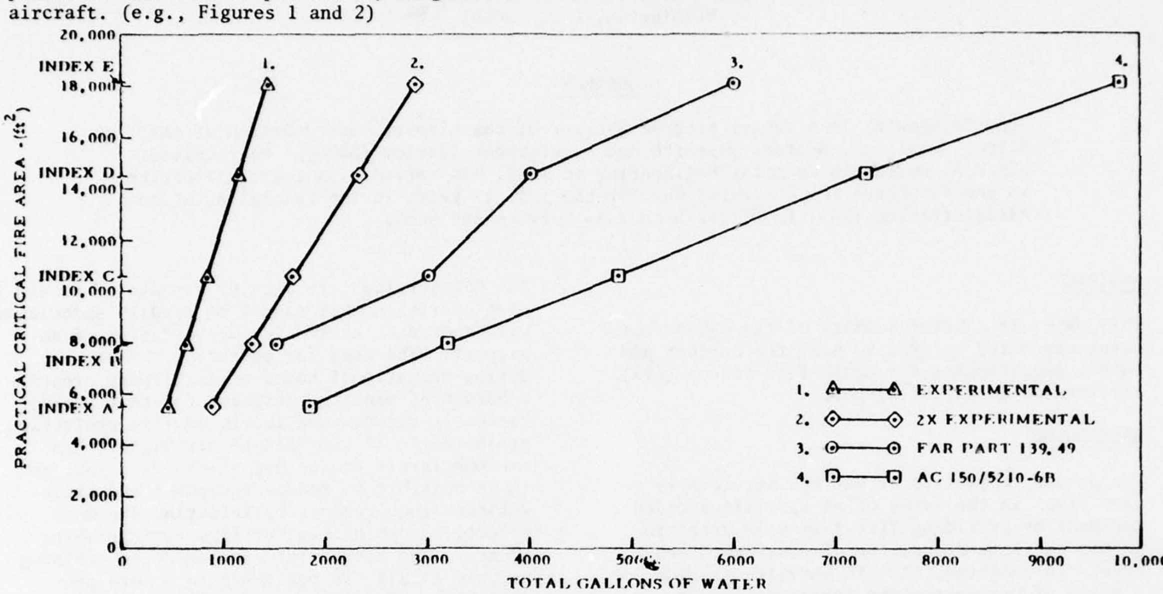

FIGURE 1. COMPARISON OF WATER QUANTITIES FOR PROTEIN FOAM PRODUCTION

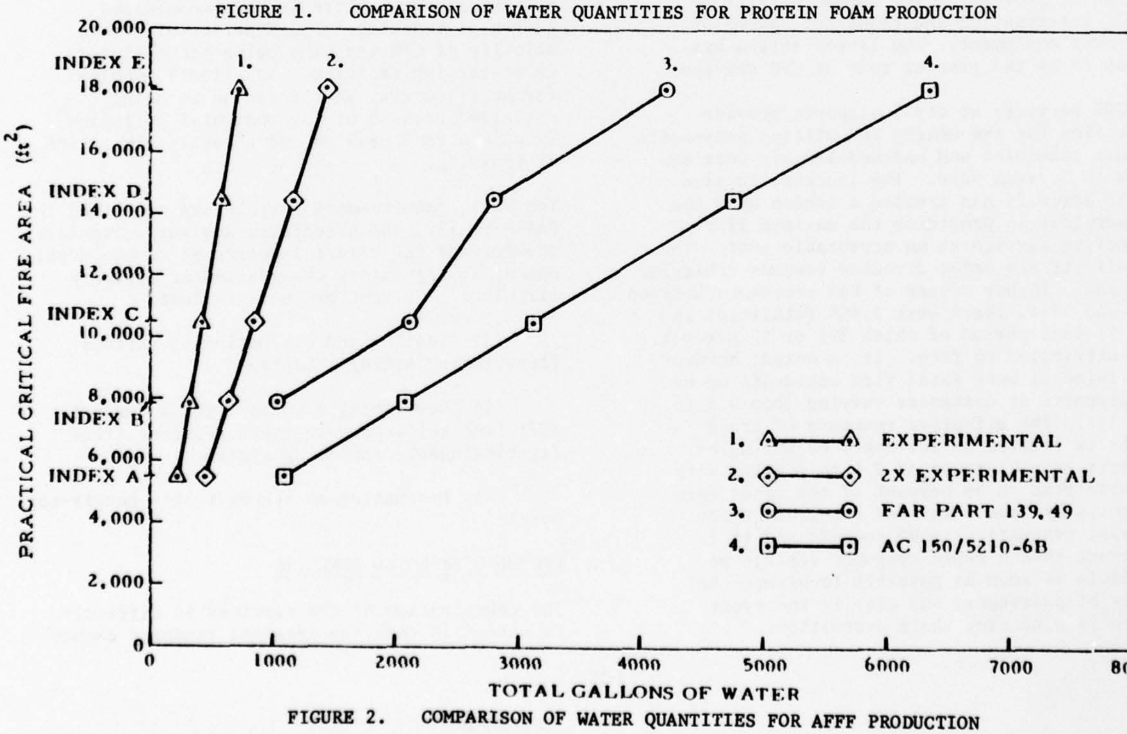

FIGURE 2. COMPARISON OF WATER QUANTITIES FOR AFFF PRODUCTION

TECHNICAL APPROACH

Extinguishing Agents

The variety of extinguishants makes it necessary to determine their effectiveness in extinguishing fuel fires. Time to control a large fuel spill fire is important to the survival of aircraft occupants. It is for this reason much R&D effort has been expended to find the best extinguishing agent(s). One agent that was developed by the Naval Research Laboratory, under the direction of Dr. R. L. Tuve, is AFFF (Aqueous Film Favoring Foam), which is a fluorocarbon surfactant. The mechanism whereby fluorocarbon surfactant function as an effective vapor securing agent is based on their outstanding effect in reducing the surface tension of water and their controllable oleophobic (oil hating) and hydrophilic (water loving) properties. These properties provide a means for controlling the physical properties of water so that it is able to float and spread over the surface of a hydrocarbon fuel even though it is more dense than the fuel. This extinguishant became known as "light water" and later became known as AFFF.

Other types of extinguishing agents are currently being used and each seems to have certain characteristics, these include; fluoroprotein foam, synthetic foam, to name a few. In order to reduce the confusion, the effectiveness of various foams were tested at our NAFEC laboratories. The objective of these tests was to determine the effectiveness of protein foam, flurorprotein foam, and AFFF. The results of some of these tests are shown in the accompanying figure (Figure 3).

A comparison of the profiles obtained using AFFF and protein foam shows that at any given solution application rate, AAF achieved the more rapid fire control time.

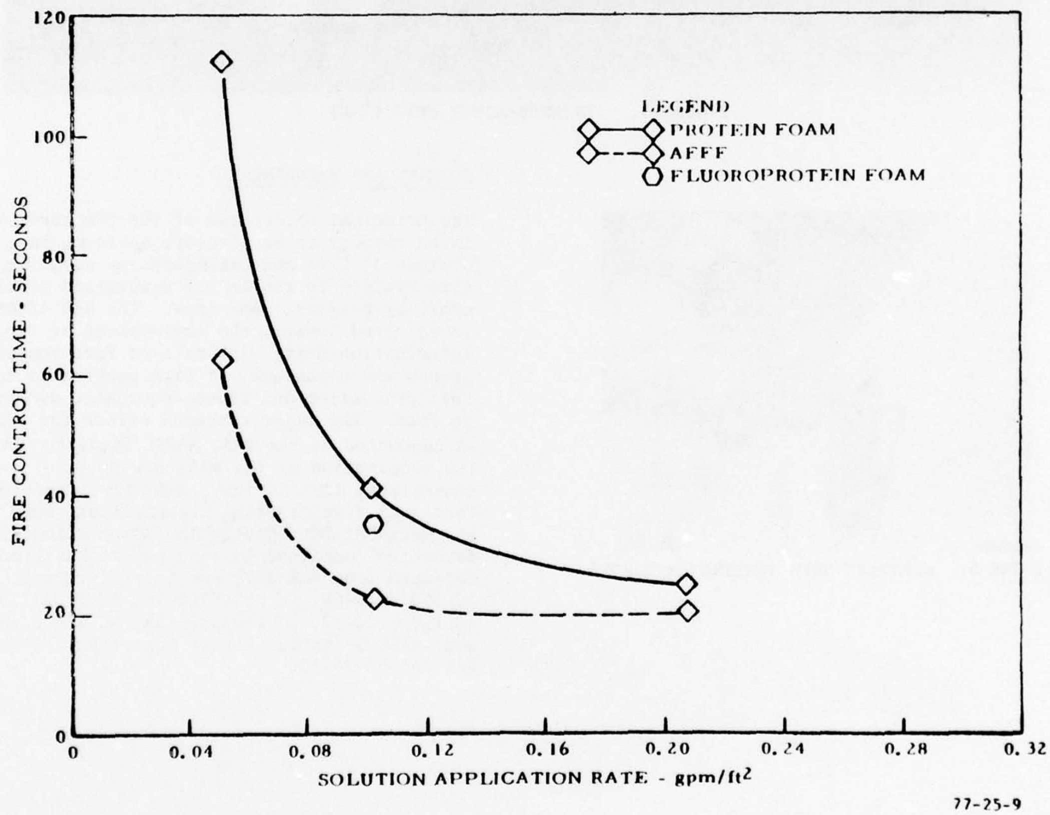

FIGURE 3. FIRE CONTROL TIME AS A FUNCTION OF SOLUTION APPLICATION RATE USING PROTEIN FOAM, AFFF, AND FLUOROPROTEIN FOAM

Evaluation of TAU (Twinned Agent Unit)

The dual agent system was developed to take advantage of dry powder extinghishant and AFFF solution discharged through a single nozzle. The dual agent system is particularly effective in securing ground pool fires with foam and combatting flowing fuel fires from a single point of discharge. The judicious use of foam and powder enables the operator to keep the thermal radiation from the flame plume within tolerable limits. This technique would not be possible without the fuel vapor recuring action provided by the foam. For this reason, the dual agent unit is rapidly becoming the system of choice for the use in rapid response vehicles in combatting complex aircraft fires. (Figure 4)

Aircraft Skin Penetrator Nozzle

The evaluation of an aircraft skin penetrator nozzle is being conducted at NAFEC. This nozzle is necessary to enable the CFR units to provide an extinguishant into a fuselage or cargo area. The test will include the determination of optimum nozzle configuration and appropriate ballistic charge to penetrate the fuselage skin. The flow rate of each agent to obtain optimum distribution pattern within cabin interior will also be determined. (Figure 5).

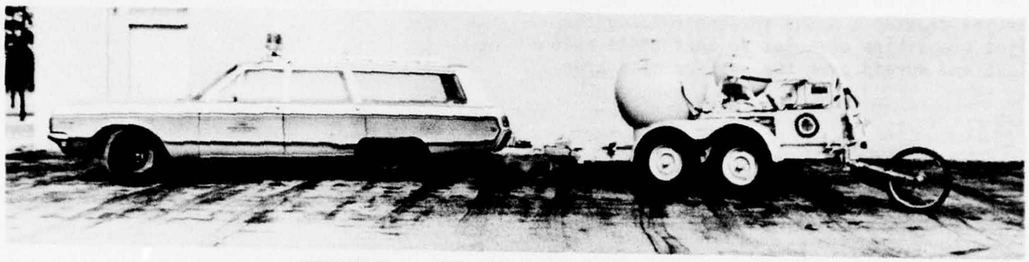

FIGURE 4. TWINNED-AGENT UNIT (TAU)

FIGURE 5. AIRCRAFT SKIN PENETRATOR NOZZLE

SUMMARY AND REFERENCES

The principal objectives of the CFR service is to respond to an aircraft accident in a minimum of time and extinguish an ensueing fire rapidly to enable the evacuation of aircraft by passenger and crew. The R&D effort is directed towards the improvement of rapid intervention unit, high rate of fire suppression agents and techniques of fire control to enhance safe evacuation and reduce equipment damage due to fire. The major research effort for CFR is conducted at the FAA, NAFEC facility with the cooperation of the military services, various educational institutions, industry, and professional fire fighting organizations such as the National Fire Protection Association. Information contained in this report has been obtained from FAR 139, Advisory Circulars; AC 150/5210-6B, AC 150-5200-16, AC 150/5210-1, AC 150/5220-10, AC 150/5325-5A, AC 150/5210-12, and NAFEC Technical Letter Report No. 77-5-LR, and FAA-RD-75-156.

AVIATION WEATHER SYSTEM PROGRAM

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BIOGRAPHY

John Hinkelman is a Program Manager in the Flight Information Services Division, SRDS and is responsible for Aviation Weather System (AWES) engineering and integration. He is a jet pilot, received a BS in Meteorology from the U.S. Naval Postgraduate School in 1954 and an MS from the University of Maryland in 1963. He was a member of the FAA NAS System Design Team from 1961 to 1963, and prior to returning to the FAA in 1976 was Manager of the Research Aviation Facility at the National Center for Atmospheric Research in Boulder, Colorado, where he was responsible for flight research in thunderstorm turbulence and jet-stream Clear Air Turbulence (CAT) areas.

ABSTRACT

Aviation weather support requirements have historically been satisfied on a problem by problem basis with little attention being given to an overall integrated system concept. Although this approach may have been generally adequate in the past, it is readily apparent that the existing framented weather support system architecture is incapable of satisfying the projected needs of the aviation community. More basic observational data are required, faster communications and dissemination techniques are needed and labor intensity must be reduced. In an effort to resolve both the near-term and long-term problems of aviation weather support, the FAA has initiated a program for the evolutionary upgrading of aviation weather services. The new Aviation Weather System (AWES) architecture will consist of four basic functional areas: data acquisition, data processing, communications, and display/presentation. Within each of these areas are a variety of required development activities which will be coordinated and integrated to provide a cost-effective total system capable of satisfying the full range of NAS weather support requirements. This paper describes the system in terms of its operational capabilities and outlines the technical engineering development program to be pursued by the FAA.

BACKGROUND

The purpose of the Federal Aviation Administration's (FAA) aviation weather support system is to provide accurate, timely, and operationally meaningful weather information to National Airspace System (NAS) users with special emphasis on the identification and description of hazardous weather situations. The existing structure at best performs this function in a marginally adequate manner but for a variety of technological and fiscal reasons, the services provided today fall well short of the optimum.

Today's system is limited with regard to the amount of information available to it, its ability to rapidly digest and disseminate those data which are operationally significant, and its capability to provide NAS users with real-time reports of weather phenomena capable of impacting the safety and/or efficiency of aviation operations. The critical elements of the existing system architecture are its high degree of labor intensity and its relatively slow communications links. Unless the basic system philosophy is altered, an increase in available information, for example, would serve only to compound the problems associated with communications, filing, sorting, analyzing and delivering meaningful products to the users in a timely manner.

In recoginition of this need for a new aviation weather support system architecture, the FAA, in mid 1977, initiated the development of a plan for the evolutionary upgrading of aviation weather support services between now and the year 2000. The evolutionary approach was taken in an effort to minimize the disruptive effects of a step-function changeover from present operational procedures and to take full advantage of ongoing system improvements in the near-term (now 1980) period. The Aviation Weather System Preliminary Program Plan was completed and approved by FAA Management in early 1978 and has been coordinated with the other Federal Agencies--National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and Department of Defense (DOD) having related aviation weather responsibilities and programs.

OPERATIONAL OVERVIEW

The AWES will provide increased operational capabilities for effectively reducing the adverse effects of weather phenomena throughout the NAS operating environment. Reliable, more accurate and more complete information, rapidly distributed in forms and formats directly useable by pilots, controllers, Flight Service Station (FSS) specialists, etc., in their decision making processes, will siginficantly improve the safety and efficiency of NAS operations. These

improvements will be accomplished through:

1. Improved radar detection, identification and tracking of severe weather echoes.

2. An increase in the number and frequency of surface observations and an improvement in their reliability through automation and quality control.

3. Automated collection, processing, and distribution of pilot reports (PIREPS).

4. A reduction in the time required to deliver operationally critical weather information to pilots and other NAS users.

5. Automated tailoring of weather information to render it more suitable for direct operational application.

6. The provision of real-time hazardous weather avoidance assistance to pilots.

7. Improvements in the accuracy of aviation weather forecasts through automation and quality control.

Each of the above listed capabilities is readily attainable within existing technology. As each of these capabilities is pursued, it will be incorporated as an interactive element of a larger integrated system--the AWES--which in turn, will function effectively in support of the NAS. The inter-relationships are depicted in Figure 1 and 2. In this regard, the following general concepts have been adopted for the improved system:

1. The major focal point for real-time collection, monitoring, interpretation and dissemination of hazardous weather information will be concentrated at the Air Route Traffic Control Center (ARTCC) Whather Service Unit (CWSU).

2. The most time-critical IFR weather information, dissemination and display functions will be concentrated at terminal facilities.

3. The System Command Center (SCC) will perform those weather-related functions associated with strategic planning and will conduct certain quality control checks of weather services provided.

4. The Flight Service Station (FSS) system's capability to provide essential briefing and inflight services (primarily to visual flight rules (VRS) operations will be enhanced and automated.

The system will use both Air Traffic Control (ATC) and weather radars to detect and track severe weather. Current weather detection capabilities will be enhanced initially by improving both en route ARSR and terminal ASR radars and by remoting National Weather Service (NWS) wsr radar data for FAA Center, Terminal (TRACON) and FSS facilities. ARSR data will also be remoted to certain FSSs. A new national Doppler radar system to be implemented in the mid-term period (1981-1984) will provide a marked improvement in the operational value of weather radar by detecting severe turbulence areas and by displaying these data directly on controller's displays. It is anticipated that the motion of the turbulent areas can be predicted for very short periods of up to 30 minutes and the projected tracks also displayed at the controller's option.

Pilot reports of hazardous weather will be collected through both the CWSU and the FSS En Route Flight Advisory Service (EFAS) positions and mutually exchanged for rapid dissemination to aircraft inflight, for preflight briefing, and for dissemination to the NWS.

An automated data collection, processing, distribution, and display sub-system will be developed for real-time dissemination of PIREPS, observations, advisories and short period forecasts to pilots, controllers and FSS specialists.

Surface (airport) weather observations will be taken and disseminated automatically at airports with approved instrument approaches but having no FAA facilities. At FSS and ATC tower sites, critical portions of the observations will be automated, augmented by humanly observed data, and automatically transmitted to users. Automated surface observing components will be modular in design to provide for installation flexibility and upgrading as required. Special detection systems for wind shear will be utilized at selected major terminals. Real-time weather satellite (GOES) cloud cover photographs will be available at the SCC, at each Center and at FSS facilities for briefing, analysis, strategic planning and hazardous weather avoidance applications.

The system will provide for rapid generation and dissemination of reliable, very short period (0-30 minutes) forecasts of hazardous weather for direct pilot and controller use. Accurate, short period (up to 4 hours) forecasts are required to support flow control activities both at the Centers and the SCC. This capability assumes a general NWS short range forecast product improvement over the next 10 years.

The 20 CWSUs (one at each Center) will perform centralized ATC weather interpretation and dissemination functions. NWS meteorologists at these positions will interpret data for use by Center, TRACON and tower controllers. Radar servere weather information will be displayed real-time on controllers' Plan View Displays (PVD) and other significant hazardous data will be displayed rapidly for dissemination to pilots.

The CWSU will be the tactical focal point for the collection of IFR PIREPs and special severe weather alerts and for their dissemination to appropriate terminals and FSSs. An appropriately programmed automatic weather data storage and display system will provide the CWSU with direct access to all surface observations, upper air data, terminal forecasts and graphics data, and

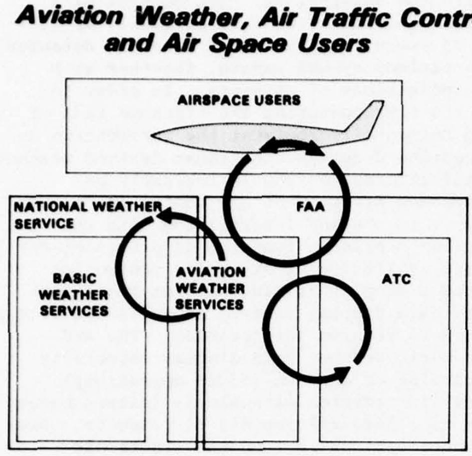

Figure 1

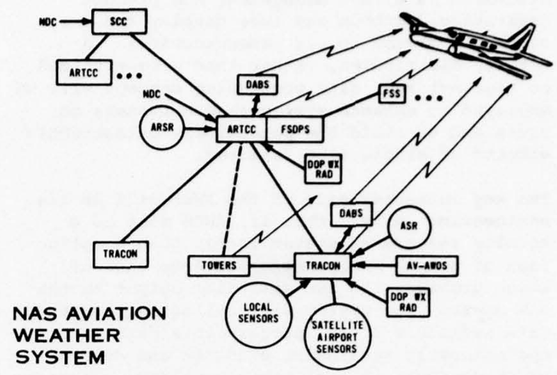

Figure 2

and severe as an entry point for PIREPs and other special data.

Severe weather data from either improved ASR or Doppler Weather radar will also be displayed on the terminal area controller's displays and remoted to BRITE display-equipped towers. Terminal area observations and other alphanumeric data will be displayed at TRACONs and local observations at towers. The center and terminal displays will be modular in design to provide for flexibility and economy in implementation. FSSs will also have displays to support briefing and EFAS functions. These displays will have access to extensive data bases to support these functions. Automatic Voice Response System (VRS) implementation in the mid-term period will enable automation of Pilot Automatic Telephone Weather Answering Service (PATWAS), Transcribed Weather Broadcast (TWEB) and certain pilot self-briefing functions.

The AWES will provide automated data processing support to each CWSU, major terminal area, and Level III FSS to support the data distribution and management functions associated with providing alphanumeric (A/N) displays at centers and TRACONS, automatic generation of very short range severe weather forecasts (extrapolations) for controllers, and to meet FSS broad data base requirements.

The supportitng communications network necessary to provide adequate rapid transfer of system data will ultimately utilize an optimum combination of NWS National Distribution Circuit (NDC) and FAA National Automated Data Interchange Network (NADIN) II 2400/4800 baud networks. The SCC and 20 Centers will have Automation of Field Operations and Services (AFOS) access equipment and, in general, the FAA will internally utilize NADIN II. Since NADIN II will not be implemented in the near-term, continued FAA use of Service A and facsimile on an interim basis will be necessary at non-automated facilities. The ultimate AFOS/NADIN interface configuration will be determined by a detailed system study of ATC and FSS configuration and loading requirements and joint interagency (NWS/FAA) plans. Figure 3 is a simplified functional block diagram of the improved system.

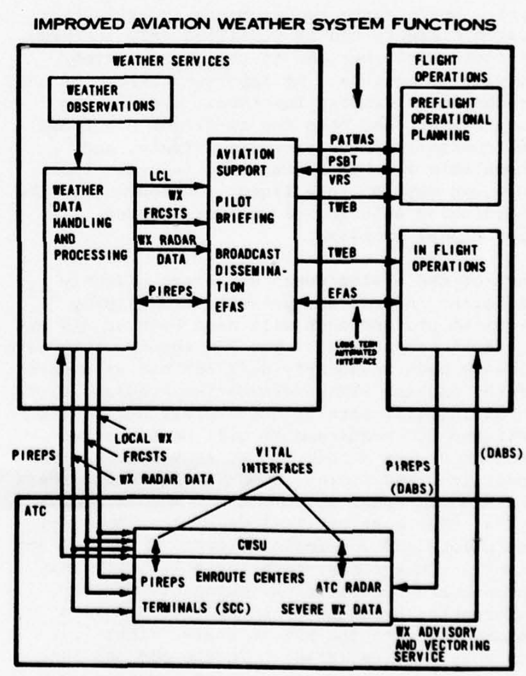

Figure 3

ENGINEERING DEVELOPMENT OVERVIEW

The AWES architecture will rely heavily on automatic data collection. Medium speed (2400-9600 bits/second) digital communications, automated data base management and product generation, cathode ray tube display and automatic ground to air communications. A totally distributed, rather than a centralized or regionalized, data processing concept will be employed to enhance system responsiveness to users and to avoid the potentially catastrophic effects of single site failures.

The key characteristic of the AWES will be its engineering unity. That is, AWES will be a totally integrated system rather than a collection of pseudo-independent elements each of which provides its own perculiar output to the NAS users. The system will collect all weather data available to it, process this data into operationally meaningful products and deliver these products in real-time to pilots, controllers, FSS specialists, etc. Thus, the system can be subdivided into four basic functional areas as decribed below.

Presentation/Display

This functional area focuses on the characteristics of the information to be provided to the system users. As such, it is the most critical area in the system design. For each user; e.g., the pilot, center controller, TRACON controller, FSS specialist, CWSU meteorologist, etc., such things as informaton content, form, format, and presentation/display control capability must be determined. These, then, become the total system performance requirements and all other system elements can be justified only in terms of their contributions to the presentation/display objectives. An important aspect of the presentation display functional area is the requirement that both the in-flight pilot and the controller have accurate, timely, and compatible weather information in order that each can make an intelligent contibution to the coordinated solution of weather related operational problems.

Each of the system users will have slightly different information presentation/display requirements and each will need both an A/N and a graphic capability. The FSS requirements have already been reasonably well defined as a part of the ongoing FSS Modernization Program which is an integral part of the overall AWES. The CWSU and SCC requirements will be satisfied through direct access to NWS AFOS System, the Modernized FSS System, GOES Satellite Recorders and Remoted Radar (both weather and ATC) displays. The most critical users are, however, the pilots and controllers (center, TRACON, and tower). In the near-term the pilot will rely on on-board capabilities, automatic weather information broadcasts, controller supplied information and the FSS En Route Flight Advisory Service (EFAS). In the mid and long terms the automated DABS ground-to-air system will ehnahce his weather information collection capability.

The presentation/display requirements of controllers are very similar regardless of whether they are in a center, a TRACON, or a tower, but so also are the constraints. The controller's graphic requirements consist primarily of outlines of storms and turbulent areas as detected by the various system radars, together with coded indications of severity. In order to avoid the time consuming and tiresome task of having to mentally register the information on two separate displays, the radar derived weather graphics information should logically be superimposed directly on the controller's ATC display. To prevent interferring with the controller's primary function of providing for the safe separation of aircraft, controller operated fading, texturing and/or quick-look weather data display control capabilities will be examined to resolve this problem. The ATC alphanumeric weather data display capability will consist of certain forced operational critical information with simple instantaneous access to a larger inventory of products. Display media options include the Electronic Tabular Display System (ETABS), Terminal Information Processing System (TIPS) a separate A/N CRT and a sterile area of the controller's ATC display.

Data Acquisition

Data acquisition is next in operational importance since it is the raw input information which dictates the content and operational validity of the output products. The FAA currently has a family of modular automatic surface observing systems under development (AV-AWOS, ALWOS, WAVE, SAMOS) which will provide synoptic weather observations at airports, and in addition, provide current observations at any time upon user request through the communications subsystem.

Automatic broadcast of observation data to pilots in flight is also a planned feature of the AWES.

A developmental model Aviation Automated Weather Observation System (AV-AWOS) was subjected to a full scale operational test at Patrick Henry International Airport, Newport News, Virginia and the results indicate that automated aviation weather observations are practical provided low cost cloud height and visibility sensors are developed. The FAA and the NWS are jointly pursuing these developments. The primary constraints in this area are the large numbers of units required, coupled with the purchases and maintenance costs per unit. Maintenance requirements must, of course, be minimal, especially at unmanned sites.

The FAA and the NWS are also pursuing the development of low cost automated observing systems (ALWOS and WAVE) for those 900 plus airports with approved instrument approaches but which presently have no weather observing capability. These systems would have more limited capabilities than the AV-AWOS but will retain the automatic broadcast feature. The initial Semi-Automatic Observing System (SAMOS)

installation is in operation at the FAA tower in Clarksburg, West Virginia. This unit provides assistance to the tower controllers who are responsible for taking observations at such locations.

The second major element in the data acquisition area is radar. Neither of the two basic ATC radars, the ASR and the ARSR, are particularly well suited to quantitative measurement of severe weather echoes, although both are more than adequate as general weather detectors. The broad vertical beam of these radars tends to compromise the validity of any quantitative turbulence or intensity calculations. A variety of developments have been completed or are currently underway in an attempt to derive valid weather information from ATC radars. NWS WSR radars are designed for weather detection and echo intensity measurement but are now 20 years old and too often down for maintenance. A variety of video remoting and processing systems are either available or under development for providing near real-time displays of radar weather data from both the FAA and NWS radars at Centers, TRACONs, towers, etc. And for the near-term period, this appears to be the best available solution. For the mid and long term periods a joint FAA/NWS/DOD national Doppler radar system is planned.

Communications

Near-term communications enhancements between the pilot and the ground will focus on more direct pilot access to weather information. In the mid and long-term Voice Response Systems (VRS) and Discrete Address Beacon System (DABS) will be employed for the real-time relay of weather information to and from pilots in-flight. Ground communication of weather information in the AWES will, in the near term, be accomplished via existing FAA teletypewriter circuits (Service A) and through direct interface with the new medium speed (2400 bits/sec., full duplex) NWS AFOS National Distribution Circuit (NDC). In the mid and long-term periods, a combination of the NDC and the FAA's NADIN II, presently under development, will be used. These two circuits will be fully capable of meeting all aviation weather communications requirements for the next two decades.

Processing

As previously noted, the AWES data processing functions will be totally distributed rather than regionalized or centralized. There will be some limited processing at each automated observing site to render the raw data suitable for local application and communication to pilots and other operational facilities. Each Center will have the capability to store a full operational weather data base, to tailor the data for direct application by users within the ARTCC area of responsibility and to service nearby towers and TRACONS. The FSS data base management and product generation functions will also be located at the ARTCCs with limited storage and retrieval capabilities at each Category III FSS. In the near-term the presently manned CWSU positions will be provided with NWS AFOS systems. This capability will then be expanded through the introduction of FSS Data Processing Systems (FSDPS). A further expanded integrated center weather data processing system capable of satisfying all user requirements is the long-term FAA goal.

Schedule

The present schedule for AWES development and implementation is provided in Figure 4. Although the schedule indicates three rather distinct phases of system evolution, the development will, in fact, be continuous in nature with improvements being implemented as they become available.

AWES DEVELOPMENT PROGRAM SCHEDULE

. SYSTEMS ANALYSIS COMPLETED	1/79
. DOPPLER WEATHER RADAR FUNCTIONAL SPECS.	1/79
. EXPERIMENTAL FACILITY ESTABLISHED AT NAFEC	2/79
. ATC TRACON/TOWER WEATHER RADAR FIELD TESTS	4/79-6/79
. ATC RADAR WEATHER ENHANCEMENT MODIFICATIONS	7/79
. PRELIMINARY AWES DESIGN COMPLETED	7/79
. RADAR SEVERE WEATHER AREA TRACKING AND PREDICTION OF SOFTWARE	1/80
. SEVERE WEATHER DISPLAY ON CONTROLLER SCOPES	7/80
. ATC WEATHER DISTRIBUTION SYB-SYSTEM	7/80
. INTEGRATED AWES DESIGN COMPLETED DABS DESIGN INTEGRATION	7/80
. DOPPLER WEATHER RADAR PROTOTYPE	7/82
. AWES PHASED IMPLEMENTATION	7/79-7/85

Figure 4

SUMMARY

The FAA is now in the process of embarking on a major new system development and implementation program. The objectives of this effort are to provide enhanced aviation weather support services in the near-term and to establish a basic weather support system architecture which will be capable of satisfying the NAS requirements for weather support over the next two decades. The majority of the system elements required for AWES development are presently available within the technological state-of-the-art. The major challenge, however, is to integrate these various elements into a cost-effective integrated system which will satisfy the broad range of weather support requirements of the entire aviation community.

COMPUTER GENERATED VOICE RESPONSE DEVELOPMENT

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BIOGRAPHY

Carey Weigel is a Program Manager in the Flight Information Services Division, SRDS, and is responsible for the development of pilot direct access concepts for the Flight Service Station Automation Program. He received his BSEE from the University of Maryland in 1966 and prior to coming to the FAA, was a Project Engineer for the U.S. Army Limited War Laboratory at Aberdeen Proving Ground where he managed navigation and surveillance systems development.

ABSTRACT

Rapid access to up-to-date weather products for preflight planning is critical to flying safety. As part of the FAA's Flight Service Station Automation Program, a computer generated voice concept has been developed to assess the feasibility of pilots interacting directly with a computer to obtain available weather and flight data on a timely basis. This paper will describe Voice Response System (VRS) technologies that have been studied, prototyped and evaluated to determine technical and operational characteristics when utilized for FSS applications. Technical descriptions of these systems are provided. Raw weather data shortcomings have been identified and activities to develop new processable weather forecast products have been initiated. A public demonstration of an initial VRS capability is underway utilizing a digitized voice response technique concatenating prerecorded, digitized and stored, vocabulary words and phrases. This capability is under evaluation in the Washington, D.C. area and brings before pilots for the first time computer generated voice dissemination of weather products. Expanded applications of VRS are anticipated for additional weather and flight products and route-oriented briefings. Future development activities regarding VRS will concentrate on new and improved weather products and capabilities such that higher quality preflight and inflight weather data can be provided General Aviation pilots. Implementation is anticipated to evolve as part of the integrated FSS Automation Program.

BACKGROUND

Pilot preflight briefing for weather and aeronautical data is an essential part of planning a safe flight. Every year National Transportation Safety Board statistics reveal an alarming percentage of weather related aviation accidents. Many of these types of accidents can be avoided when pilots acquire and take appropriate action regarding pertinent and up-to-date hazardous weather information - before they leave the ground. The concern for rapid access, updating and availability of these often critical weather products, particularly during the pilots preflight planning process, has been a prime reason for the development of the Federal Aviation Administration's (FAA) new concepts of pilot briefing. The substance of this paper will describe our development approach to one of the most promising preflight briefing techniques on the horizon, computer generated voice response.

The FAA is currently initiating a program to automate the Flight Service Stations through the application of high speed data communications and computer processing techniques. The data required will be collected, formatted and edited, distributed and displayed by automatic means. The Flight Service Specialist will be provided with a video display and keyboard to retrieve data in a standard format from the national meteorological and aeronautical data base. These capabilities will greatly enhance the operation of the specialist function. However, in order to meet future demand and provide quality preflight briefings without substantially increasing the FSS staff, a means must be made available such that pilots can completely or partially brief themselves. This aspect of the automation is generally referred to as "direct user access" and employs concepts that enable a pilot to directly communicate with the computer data base and select those products needed to satisfy his briefing requirements. These direct user access techniques are vital to the cost effectiveness of the overall automation program.

One of the primary candidates for pilot direct access is computer generated voice dissemination of weather products. The computer generated voice or Voice Response System (VRS) would be located in major population areas and be accessible via the existing telephone network. For the purposes of the FSS development and application, the voice response capability is defined as a system that can automatically, and in a natural sounding voice, read to the pilot

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information which is digitally assembled and stored in a computer data base.

The FSS has many potential applications for a voice response system since its major function is to disseminate numerous types of weather and flight data reports. Currently, some FSSs maintain taped pre-recorded messages such as the Transcribed Weather Broadcast (TWEB) for inflight dissemination over a VOR or beacon frequency and the Pilot Automatic Telephone Weather Answering Service (PATWAS) accessed via the telephone network for preflight briefing. These products require substantial manpower in order to generate them and maintain their currency. The VRS, when fully developed, can provide these services cost effectively and automatically. In addition, a new feature allowing pilots to select particular reports for locations across the country can also be made available. Future applications for such services as automatically prepared route briefings and automated flight plan filing with VRS prompting are possible. All that is needed is well-thought-out development, building block implementation and careful integration of user requirements.

The application of voice response to the FSS requirement areas noted above presents some very unique challenges to design engineers and, in particular, applications programmers. Voice response systems are available commercially today; however, typical applications are very staightforward, generally limiting user inputs to numeric entries and retrieving/speaking data that is very terse, limited in vocabulary and under very strict control in regard to format and content. Many examples are available. The most familiar is probably the bankteller or salesperson verifying a credit transaction, who enters an account number and receives, automatically, the verbal computer readout of the requested information. Those systems are very effective; however, from a technical standpoint, they are very well bounded having the characteristics noted above and seldom exceeding 100 to 200 words of vocabulary.

PRODUCTS/EXPECTED RESULTS

The purpose of the FAA's development in this area is to determine if VRS is operationally feasible, establish support and source data requirements to drive a VRS capability, evaluate alternative VRS technologies and evolve an implementation strategy and plan such that VRS can operationally be made available to pilots on a widespread, nationwide basis. Specifically, end products will include:

. Operational prototypes of selected VRS technologies.

. Test and evaluation reports verifying operational feasibility and designating needed design parameters.

. National plan for VRS implementation.

. Procurement package of requirements and specifications.

At this time, based on public response to date, we fully anticipate pilot acceptance of the basic concept and are in the process of initiating activities which will lead to integration of a VRS capability in the FSS Automation program.

DEVELOPMENT APPROACH

In the last two years, several parallel development activities have been directed at the application of voice response technology to the pilot direct access function. The general approach has been to learn something about voice response techniques, determine the impact of current weather data formats, etc., on potential VRS applications and try to assess user acceptance and general operational feasibility. To support this approach, three task areas were established:

A. Develop voice response systems-hardware and software.

B. Study weather data characteristics and vocabulary requirements.

C. Define and evaluate operational capabilities, such as features, protocols, formats and content.

A. Voice Response System Development

Computer generated voice response systems typically consist of a vocabulary of words and/ or phrases, a data base of information to be spoken and a means of assembling the required vocabulary items in such a manner as to provide coherent responses to the user. Two general categories of voice response technology are currently available: synthetic voice response and digitized or waveform coding. Synthetic systems utilize a set of parameters which describe a basic speech waveform, such as frequency content, to create appropriate utterances. These utterances when programmed together "sound" like a person speaking. The technique is totally artifical. The hardware device that creates the utterances can be best described as an electronic analog of the human vocal system. The digitized or waveform coding systems on the other hand produce a voice output that is based on actual recordings of human speech. The original speech signal is represented by digitally recording its amplitude as a function of time. The digital representation of the word is then stored in the computer for later recall. Various configurations of each of these technologies can be acquired essentially as "off-the-shelf" items; however, the uniqueness of our applications dictated a development effort to tailor the voice response system design specifically to the complex software required for weather data processing. It was decided to build both a synthetic and digitized VRS such that a technical and operational evaluation could be made regarding each respective system for the FSS applications.

Synthetic VRS

A synthetic voice system was developed for the FAA by the MITRE Corporation, METREK Division, at McLean, Virginia, and employs as the basic speech device the VOTRAX ML-1, built by the Vocal Interface Division of Federal Screw Works, Inc. The VOTRAX synthesizer utilizes one of the fundamental concepts in speech technology called phonemes as its waveform parameter. A general discussion of a coding scheme based on this parameter provides an example for understanding the general concept of synthetic operation.

Every spoken language consists of a set of fundamental sounds called phonemes. These sounds are strung together forming vowel and consonant sounds in such a manner as to make up the spoken language. For example, the vowel sound "i" as in "bite" is produced by the phonemes "ah" and "ee". Most languages consist of less than 200 phonemes, with the number in common usage ranging from 50 to 60. Slight variations can be given to each phoneme by changing the stress (i.e., angry, calm, or happy) and duration (how long the particular phoneme takes to pronounce). Stress does not vary by much at the phoneme level; limiting the stress to four different values is adequate to cover most speech. Duration for most phonemes is covered by range of 25-100 ms. Using 15 ms steps from 15-240 ms (16 steps) is sufficient to satisfy duration range requirements.[2] Some synthetic systems may include other variations as phoneme modifiers.

A data rate can be determined for this basic encoding method. For example, lets assume each encoded value corresponding to an eventual utterance contains three parameters: the encoded phoneme, its stress and its duration. Since the number of phonemes is less than 200, the phoneme can be encoded as an 8-bit integer. Stress, which can be one of four possible values, is encoded as a 2-bit number. Duration can have one of 16 possible values, thus requiring a 4-bit integer. This method gives a total of 14 bits for each encoded utterance or sample. Since phonemes are typically greater than 25 ms in duration, the number of samples per second will be 40 or less, giving a maximum data rate of 560 bit/s for a synthetic system using phonemes as the encoding parameter.[2]

The synthetic test system configuration assembled for the FAA is shown in Figure 1. Each phoneme command in this system consists of 2 ASCII characters, although only 12 of the 16 available bits are used. These bits contain the information for the basic encoding parameters as the phoneme, amplitude, duration and stress. This particular unit is only capable of uttering approximately 80 phonemes; however, that appears to be adequate to speak understandably. Typically, there are roughly as many phonemes required to generate a word as their are letters in the word.

For evaluation and demonstration purposes, the VOTRAX system currently delivers up-to-date hourly surface observations, terminal forecasts and forecast winds aloft to calling pilots. This system utilizes vocabulary translation tables to convert data supplied by the Weather Message Switching Center (WMSC) in Kansas City to the character structure required by the VOTRAX units. The computer which accomplishes these tasks is a DEC PDP 11-70 processor. Tests and demonstrations with this system have received favorable results. Pilot ability to understand and copy information spoken by the VOTRAX has been good. The primary drawback for general public applications is the pronounced "classical computer robot voice" that is characteristic of its sound.

Digitized VRS

The general concept of operation for a digitized VRS is shown in Figure 2. A person, on a one-time basis, records a vocabulary of words and phrases. These recorded vocabulary items are digitized according to an encoding scheme and entered in the computers memory. At a later time they are retrieved from memory, strung together with other words as required and converted from digital to analog information for voicing to the pilot. The quality of voice produced by the system is very much a function of the complexity of the digital encoding technique selected.

Digital waveform coding requires that the amplitude of the speech signal be sampled as a function of time. Sampling is accomplished using an analog-digital converter which measures the signal amplitude at regular time intervals and produces a series of binary numbers representing the signal amplitude at each interval. For a sampled waveform, the highest frequency in the waveform which can be reproduced qualitatively is called the Nyquist frequency, which is equal to one-half of the frequency or rate of sampling. Experiments have shown that acceptable quality speech can be reproduced with a speech band-width of 3KHz, thereby requiring a sampling rate of 6KHz or greater.

The reproduction process is basically the reverse of the recording and encoding process. First, the reproduction process obtains the digital representation of the waveform from the vocabulary storage medium. Retrieved digital samples are converted to an analog waveform by a decoder, such as a digital-to-analog converter. This decoder applies the inverse of the encoder function to each sample to reproduce the original waveform. The basic operations for waveform coding are shown in Figure 3.[1/]

Typically, most systems use a sampling rate between 6 and 8KHz; however, the final data rate or bits/second that are required to digitally encode the speech varies greatly between

1/ From Thordarson, "Design Guidelines for a Computer Voice Response System", Computer Design, November 1977.

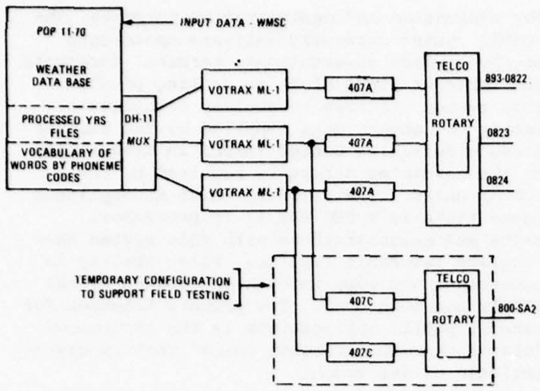

Figure 1 - Synthetic Voice Response System

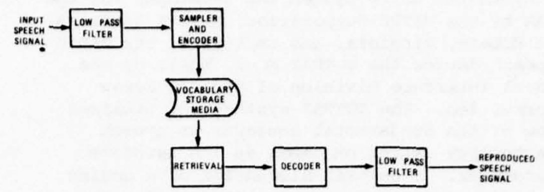

Figure 3 - Digital recorder/reproducer. Speech signal is first filtered to remove high frequency components unnecessary for quality speech reproduction. Cut off frequency of filter is 3KHz. Filtered signal is then sampled at a rate of at least twice cutoff frequency (6KHz) and samples are stored on digital storage medium such as magnetic disc. Speech reproduced by retrieving speech samples and decoding them by applying function which is inverse of the encoder function. Resulting signal is filtered to remove distortion introduced by sampling process, giving reproduction of original signal.

DIGITIZED VOICE RESPONSE SYSTEM

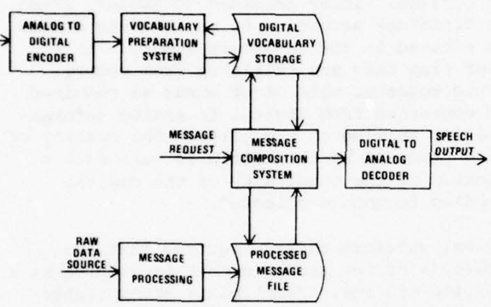

Figure 2

the chosen encoding techniques. Pulse code modulation (PCM) is the simplest and most widely known waveform coding method. Using a conventional analog digital converter, encoded samples are a linear integer representation of the waveform amplitude; if signal amplitude doubles, the corresponding integer sample value doubles. Accuracy of the integer representation in a PCM or waveform coding system depends on a quantity called the step size--the difference in signal amplitude represented by the successive integer sample values. This step size determines the smallest variations in the input signal which will produce a variation in the encoded samples. The smaller the step size, the more accurate the signal reproduction will be. Unfortunately, a small step size results in a large number of bits required to fully describe the sampled signal. This is important since sample size multiplied by sampling rate gives the required data rate for a PCM system.

Although PCM systems are the simplest designs to implement, their data rates are the highest. A sample size of at least 11 bits (data rate of 66K bits/sec when sampling rate is 6KHz) is required to achieve high quality speech reproduction. With this sample size, the distortion introduced by the sampling process is barely perceptible to the listener. Higher distortion levels are tolerable; however, a sample size of less than eight bits (data rate of 48K bits/sec) will introduce more distortion than is acceptable by the majority of listeners.[2]

A decrease in data rates for PCM systems can be obtained through the use of numerous data compression techniques. Some of these techniques dynamically vary the step size, some compare successive sample values for predictable correlation properties. Many techniques combine the various approaches but all have the same purpose--reduce the bit rate required. (It should be noted that the choice of encoding techniques directly affects the size and throughput required for the storage medium). Data rates for the encoded speech signal vary considerably from one technique to the next. The rate depends on the desired signal to voice ratio and, in some cases, the sophistication of the algorithm used to vary the step size As in most system designs, a trade off always exist. In this case, the trade off is reduction in data rate vs. complexity and cost of step size algorithms.

Two digitized voice systems have been developed for the FAA by the Department of Transportation's "Transportation System Center (TSC)" with software contract support from Input/Output Computer Services, Inc. One system is a single channel system for controlled pilot testing; the second system is a multichannel system that can conduct twenty simultaneous pilot briefings with live and current weather data. The multichannel VRS functions as the general waveform coding description presented above; its system configuration is shown in Figure 4. The FSS Development Data Base processor is located at the MITRE Corporation facility in McLean, Virginia and the VRS subsystem is located at TSC in Cambridge, Massachusetts. It should be noted that these computer systems are the heart of the development

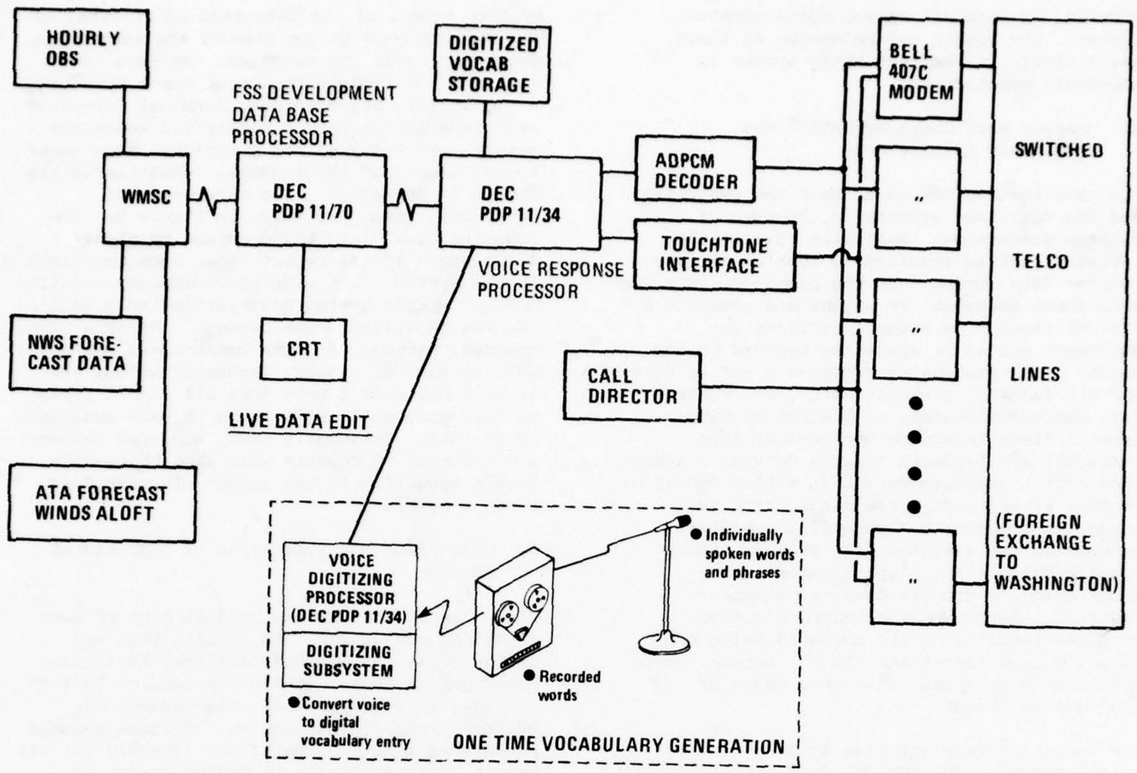

Figure 4 - Multichannel VRS System Configuration

activities regarding pilot direct access and as such support much more than just the VRS demonstration.

Pilots interact with the VRS (a DEC 11/34 computer-based system) using 12 key TOUCHTONE[R] equipped telephones for data entry. Their request for data is transmitted to the FSS Development Data Base which retrieves the required weather data (i.e., the words and phrases spoken for the particular weather report) and sends it back to the VRS. The VRS looks up the digitally encoded speech files corresponding to each of the specified words and phrases in its vocabulary, converts the vocabulary items to its analog (audio) form and routes it to the pilot through his telephone. The VRS can accommodate up to twenty pilots in this fashion.

Current raw weather data is received periodically by the FSS Development Data Base Processor via a 2400 bps synchronous communications line from the Weather Message Switching Center (WMSC) computer at Kansas City. The information is stored in a circular file called KCW. All of the weather data delivered by the VRS has its origin in this file. The raw weather data conversion process uses a dictionary look-up procedure to translate the textual data into binary representations. The binary information represents the position and length parameters that correspond to digitized words and phrases which are stored on the VRS computer's fixed-head disk.

As each weather report or forecast is processed, it is stored in another file on the FSS Development Data Base disk unit. This file, called the Universal Data File, or UDF for short, contains all of the elements required to perform the processing of the raw weather data into "retrievable" VRS messages.

Approximately 725 words and phrases are contained in the system vocabulary. These items were recorded by a professional radio announcer and then digitized onto the VRS computer's fixed-head disk unit using a process known as Adaptive Differential Pulse Code Modulation (ADPCM). The ADPCM process reduces the normal 11 bit PCM speech sample to 4 bits. Using this technique, one second of speech results in 24000 data bits using a sampling rate of 6KHz. On output, the code words corresponding to speech utterance of a particular weather report or message are decoded and converted from their digitally stored form to their analog representation, thereby, reproducing the original speech sounds.[1]

The speech quality produced by this system is quite good. The sound is natural, pleasing, completely intelligible, and of high quality.

However, as with all speech concatentation systems, the speech can be choppy at times, particularly if the text being spoken is awkwardly constructed.

B. Weather Data Characteristics and Vocabulary Requirements

One task that is common to both the synthetic and the digitized systems is the area of message processing. Basically this is the software that is required to look at all the weather data coming into the computer, determine what those messages are saying and generate a list of respective vocabulary items (or phonemes) needed to speak the reports to the pilot. This processing requires a set of rules for the formats, contents, etc., for the raw data and unfortunately is subject to many problem areas regarding the weather data currently available in today's Service A system. Very little standardization in either format or content exists. This standardization is essential in order to accomplish computer processing and a system like the VRS cannot operate without it. Typical anomalies encountered in the raw data are shown in Figure 5. Much of these standardization problems result from the messages being constructed from free text. In the future, these messages must be generated in a computer processable format.

The length of messages also is important for voice response applications from the standpoint of pilot ability to listen and absorb information. On a printer for example, many long messages can be printed and the pilot can visually scan the reports to obtain his required information. The VRS on the other hand would take a very long period of time to read long messages, such as an area forecast, and the listener's ability to assemble in his mind all the elements of information critical to him is doubtful. Therefore, we believe that VRS messages need to be fairly concise. Some testing has been accomplished to verify this consideration.

TYPICAL ANOMALIES ENCOUNTERED IN RAW DATA

- LEGITIMATE WORDS, OVERLOOKED IN VOCABULARY PREPARATION
- MISSPELLED WORDS, INCLUDING WORDS RUN TOGETHER
- NON-STANDARD VARIATIONS IN SPELLING OR ABBREVIATIONS
- ERRONEOUS CHARACTERS WHICH MUST BE DELETED
- NON-UNIQUE EXPANSIONS OR CONTRACTIONS
- TRANSPOSED ENTRIES ON KEYBOARD (UPPER-LOWER CASE)

EXAMPLES

- *AND* IS A LOCATION IDENTIFIER FOR ANDERSON, S.C., AS WELL AS THE CONNECTOR "AND"
- *NE* COULD BE NORTHEAST, NEW ENGLAND, NEBRASKA
- *OCCASIOSIONALLY* – OCNLLY, OCNLY, OCLY
- *ADVISORY* – ADVSY, ADVY, ADZY, ADV

Figure 5

Another aspect of the data that is critical to VRS applications is the size of the vocabulary needed to speak the messages. We have found that for the implementation of three products; i.e., surface observations, terminal forecasts and winds aloft, approximately 725 words and phrases are required for a national data base assuming most of the location identifiers[2/] are spoken in phonetics. The categories of vocabulary items are shown in Figure 6. The required vocabulary would expand to almost 4,000 items if all report types were contained in the system. The size of vocabulary significantly impacts system cost particularly utilizing the digitized voice concept. At this time, however, because of other constraints mentioned such as size of report, standardization, etc., it does not seem likely that all report types as they currently exist would be made available on the VRS. Presumably newly designed formats and contents of reports will also bring with them a reduction in the number of vocabulary items required.

C. Definition and Evaluation of Operational Concept

Pilot use of the VRS has been an area of much study and evaluation. An initial test was conducted at the National Aviation Facilities Experimental Center (NAFEC) in January 1977 to consider various protocols and formats for weather product presentation. Because message processors were considered not feasible for all report types initially, a beginning set of products consisting primarily of hourly surface observations, terminal forecasts and forecast winds aloft were developed. These reports did not consist of enough information to enable the VRS to present a PATWAS or TWEB type of briefing; however, it was determined that these 3 products could effectively provide a pilot with early flight planning information sufficient for a go,

2/ A location identifier takes the place of the name and location of an airport, navigation aid, weather station or air traffic control facility. The VRS utilizes three-letter location identifiers for input or required weather reporting and forecast locations. These can be found in the NOAA publication "Airport/Facility Directory".

BASIC WORDS (NUMBERS, LETTERS, ETC.)	312
WEATHER DESCRIPTIONS	247
GEOGRAPHIC DESCRIPTORS	35
CONTRACTIONS	85
WEATHER REPORTING STATION NAMES.........	12
CONTROL PHRASES (HELLO, ENTER, ETC.).......	34
	725

Figure 6 - Vocabulary Requirements For Hourly Observations, Terminal Forecast, And Forecast Winds Aloft

no-go to the airport decision. Selection of specific reports necessitated the use of a TOUCHTONE® phone rather than a rotary dial phone since the pilot had to enter information into the computer in order to get a response. This capability is referred to as interactive voice response and utilizes the basic three-letter identifiers as an input on the pushbutton keys to specify locations. Numerous briefing formats and touchtone protocols were studied. Controlled tests with approximately 60 pilots indicated that the concept was feasible, desirable and effective. Those tests also indicated that additional products were desirable; however, such reports like area forecast were too long to be used effectively. A concept of route processing was evaluated resulting in the conclusion that simply retrieving reports along the route was not suitable because of the excessive verbage presented to the pilot. Clearly a new weather product is needed to facilitate VRS route briefing.

The development approach after 1-1/2 years of effort provided the establishment of several VRS test systems with which to gather information on raw weather and flight data reports and to perform controlled testing on operational concepts proposed for VRS. General pilot and FAA operations support began to build after the NAFEC tests and various user organizations were urging the FAA to implement the concept as early as possible in the automation program. As a result of the success and interest at this point, it was decided to publicly demonstrate a limited initial VRS capability under operational conditions in the Washington, D.C. area to assess the pilot reaction to the concept.

VRS PUBLIC DEMONSTRATION

The demonstration utilizing pilots in the Washington, D.C. area brought first exposure of FSS weather data dissemination via a computer-controlled voice response system to the public. The primary purpose of the test was to determine overall pilot acceptance and usability of the concept; i.e., does it satisfy or partially satisfy a pilot's needs and can he use it effectively? Much additional information was also planned for acquisition during the demonstration and a subsequent user survey with particular interest regarding the acceptability of pushbutton keystroking and pilot comments on presentation formats and protocols. Data gathered before, during and after the VRS test at the Washington Flight Service Station at Leesburg will be analyzed to determine the impact of the VRS on the existing FSS operation. The results of all the data gathered will be used in the overall development and implementation planning of VRS in the automated FSS system.

The multichannel digitized VRS previously described was reconfigured to support the demonstration. Twenty foreign exchange lines from Cambridge, MA, to Washington, D.C., were installed to provide access to pilots from the Washington, D.C., local calling area

Figure 7 - VRS Toll Free Access Area

(Figure 7). Three weather products are provided on the system; hourly surface observations, terminal forecasts and forecast winds aloft (Air Transport Association (ATA) Grid Winds--prepared by National Meteorological Center for the airlines). The system is simple to operate, using a prompted format of presentation with the computer asking pilots for required inputs.[3] This approach seemed a logical choice for the initial exposure to pilots since it minimizes required pilot knowledge of the VRS operation. The advertised capability of the briefing was for early flight planning and "go-no-go to the airport" decision-making. In all literature released on the system, it was clearly indicated that the VRS did not contain all the weather and flight data available for complete preflight planning and, as such, was not intended to completely replace the specialist briefing. The FAA feels strongly that pilots should obtain all available products when conducting a preflight briefing, including SIGMETs, AIRMETs, NOTAMs, PIREPs, and a general weather synopsis.

In preparation for the demonstration, a special capability for editing data that fails the automatic processors was developed. As noted in a previous discussion on problems with Service A weather data, sometimes a weather report cannot be automatically translated from its raw textual format into a processed "retrievable" format. This condition can arise if the data items are garbled, misspelled, ambiguous, or the corresponding speech utterance is missing from the vocabulary. In that case, the weather report is sent to an edit station where it is manually corrected by a data editor. The corrected report is then filed by the editor for reprocessing by the raw weather data conversion routines. This capability was provided for the demonstration system since at the time the demonstration was planned, there was uncertainty regarding what percent of reports could ultimately pass the automatic processors.

Thus far, initial data editing results indicate that a very low percentage of reports default to the edit position. It is projected that the message processors currently operating are sufficient to support a three-product VRS with no editing services needed. Those messages which cannot be processed are simply voiced as "not available". The system was made available to pilots 7 days a week, 14 hours a day (limited only by the requirement for editors). The total demonstration period was originally planned for 4 months but has been extended. The system went into operation on April 15, 1978, and is currently scheduled to remain in operation through the 15th of September. The VRS system at TSC is shown with operator in Figure 8.

Figure 8 - VRS Test System at TSC

At the date of the writing of this paper, the questionnaire to pilots has just been mailed out. A complete description of the results of the questionnaires and collected system data will be available in approximately 6 months. We do know that the general response to date is outstanding. Many letters and phone calls have been received in support of the concept. Despite the estimate that less than half of the pilots in the area have touchtone telephones, pilot calls to the system have been substantial. The number of callers varies considerably based on prevailing and forecasted weather conditions; however, an average of 400-500 calls are received daily. Typical comments received generally indicate pilot interest in more products being made available, particularly NOTAMs, weather warnings and icing information. Numerous pilots have expressed an interest in a shortened, nonprompted format for the "experienced" users. We have tested one design of such a format in conjuction with a prompted format that allows the system to be accessed in either mode very successfully. We concur in that thinking. The important point thus far is that it appears that pilots feel the basic concept is good. That indication alone supports additional development toward VRS implementation. It is too early at this time to assess any impact on the current FSS operations.

FUTURE DEVELOPMENT AND APPLICATIONS

Earlier in the text, numerous problems, primarily in the raw weather data, were noted. These problem areas are the focal point of future development in VRS. In order for more products to be spoken and conventional PATWAS/TWEB messages to be VRS-generated, raw reports will need to be standardized in some type of computer processable format. Eventually, it would be desirable to have the capability of accepting a route request from a pilot, along with some parameters he considers critical to his qualifications and type of aircraft, and be able to read back for the pilot a synopsis of key weather information along his route of flight. Currently, a joint FAA/NWS program is being formulated to develop and evaluate candidate data structures which could provide forecast data and possibly some observed data in such a manner.

Additional development is planned to accommodate new weather report types and some flight data reports such as NOTAMs and PIREPs on the VRS. Last spring, NWS introduced Convective SIGMETs and is considering issuing weather warnings by state. Software work is planned such that these reports can be processed in the near future. Some changes and additions to the existing system will also be developed pending final analysis of the public demonstration results. A combination short and prompted format is needed and will be considered for implementation in the future. Development will also continue using the VRS prompting for interactive touch-tone flight plan filing experiments.

Some expansion is planned for the test voice response systems, however, we do not anticipate any FAA supported development of voice response technology per se. Many scientific efforts are underway in the computer industry to upgrade and improve VRS techniques and equipment and commercially available units of good quality are making their way to the market place. We believe industry can support implementation of acceptable systems at this time and the outlook for a future abundance of manufacturers with an acceptable VRS capability is very promising.

SUMMARY

Development of VRS over the past year has progressed very well. Two technology prototypes are operating reliably and are available for evaluation and demonstration. Preliminary results have indicated that from an operational feasibility standpoint, the digitized VRS is preferable to the synthetic approach primarily because of the superior voice quality. Cost analysis for the two systems indicates they are reasonably cost comparable for an installation that would service a substantial number of users (20-30 channels). NWS source data (raw weather text) problems have been defined and activities to provide future solutions to these problems as well as create completely new

weather products are underway. A public evaluation/demonstration is successfully in progress and pilot support for the concept is building.

In general, applications for VRS are unlimited. Within the foreseeable future in the FAA, VRS can be expanded to provide automatic message generation for FSS radio outlets, terminal information systems, nontower dissemination systems, and automatic weather observations. Other applications undoubtedly will evolve. Outside the FAA, the public demonstration has opened up many possibilities. Numerous business, agencies and technical companies have called the FAA for information on the VRS because they feel the voice quality is excellent and has potential applications in their business. Up to the start of the demonstration, VRS has carried a stigma regarding its use for the general public--always a concern that the voice quality would not be acceptable to nontechnical persons. We believe our VRS development has put that concern to rest.

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ADVANCED INTEGRATED FLIGHT SYSTEMS TECHNOLOGY PROGRAM

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Federal Aviation Administration

BIOGRAPHIES

Edward M. Boothe is an Aerospace Engineer and pilot with the Aircraft Flight Safety Branch, Aircraft Safety and Noise Abatement Division. He is responsible for research and development programs in the area of transport safety and is Program Manager of the Advanced Integrated Flight Systems (AIFS) program. AIFS is specifically concerned with active controls and advanced digital avionics. Before joining the Federal Aviation Administration (FAA), Mr. Boothe was an Aeronautical Research Engineer and Engineering Test Pilot with the Calspan Corporation where he conducted flight research projects using variable stability airplanes. While with Calspan, he also conducted flight demonstrations on stability, control, and handling qualities at the United States Air Force and United States Navy test pilot schools. Mr. Boothe's undergraduate studies were with the George Washington University and later he earned his MS in Aeronautical Engineering at Texas A&M University.

Larry K. Carpenter has been employed for the past 6 years with the Aircraft Safety and Noise Abatement Division since graduating from West Virginia University in 1972 as an Aerospace Engineer. For the past 2 years, Mr. Carpenter has worked in the Aircraft Flight Safety Branch and helped to establish the FAA's Advanced Integrated Flight Systems program which is concerned with the development of future airworthiness criteria for advanced active control and digital avionics technology. The primary areas of his responsibility as an Associate Program Manager are Federal Aviation Regulation impact/guidance criteria, structures, and flight characteristics and performance. Initially, Mr. Carpenter was employed with environmental research in the areas of sonic boom, noise abatement, and aircraft emission control. In addition, Mr. Carpenter contributed significantly to the establishment of the FAA's research and development aviation security program which has emphasis on development of techniques and devices to detect explosives in the aircraft/airport complex.

John E. Reed received a BAS Degree in Electronics in June 1956 from the University of Houston, Houston, Texas. From July 1956 to September 1958, he was employed as a Microwave Systems Engineer at Collins Radio Company, Richardson, Texas. From September 1958 through February 1968 at Martin-Marietta Corporation, Denver, Colorado, he was a Project/Systems Test Engineer in the Titan series of missile and space launch vehicle systems. From February 1968 to the present, Mr. Reed has been employed by the Federal Aviation Administration, Systems Research and Development Service. He has been in Associate and Program Manager positions in the Communications Division, "Aircraft Separation Assurance" program; Approach and Landing Division, "Microwave Landing System" program; and presently, the Aircraft Safety and Noise Abatement Division, "Advanced Integrated Flight Systems (AIFS)" Technology Program. As an Associate Program Manager in the AIFS program, he is responsible for the projects related to digital flight control and avionic systems.

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ABSTRACT

Driven by the need for improved aircraft safety, performance, and reduced direct operating cost, modern system development has provided the feasibility for application of digital flight control and avionics, active controls, and control configured vehicle features. A stimulus to accelerate industry implementation of advanced technology is provided by the national policy for energy conservation. Such implementation will impact derivative transport aircraft in the near future. Airworthiness standards and certification procedures for transport aircraft must keep pace with technology. Therefore, a Federal Aviation Administration (FAA) Advanced Integrated Flight Systems (AIFS) Technology Program has been established to develop expertise and provide generic information needed to evaluate and advance the aviation safety regulatory system and policies relative to the emerging advanced technologies. This paper presents a limited description and status of those projects currently in progress.

BACKGROUND

In recent years following the 1973 oil embargo, jet fuel prices have risen about 200 percent (from 13 cents per gallon in 1973 to 35 cents per gallon in 1977) (reference 1). The increase in fuel price presently accounts for 20 percent of the total operating cost for aircraft as opposed to only 10 percent in 1973. This increase in operating cost has caused significantly greater emphasis on aircraft fuel efficiency and has provoked renewed interest in fuel conservation through improving aircraft design and developing new operational procedures.

Advanced aerodynamics and the potential for reduced structural weight through the use of active control technology (ACT) offer opportunities for improved fuel efficiency (reference 1). The emerging implementation of ACT, however, requires sophisticated airborne computational capability, Because of the rapid advances of the last two decades, digital microcircuit technology is meeting this computational challenge. One of the most significant advances is the continued increase in the number of equivalent components that can be placed on a single semiconductor chip (reference 2). The resulting decrease in digital processor size allows enormous computational capability to be designed into digital avionic systems.

The cost per chip remains relatively constant, which means the cost per function is dropping significantly as shown in Figure 1 from reference 3. Chips are now being developed with 25,000 to 30,000 transitors, and some of the factors allowing for this increased density are beginning to reach their theoretical limits. However, doubling of capability every 2 years for the next several years is likely and will offer even greater possibilities for the future.

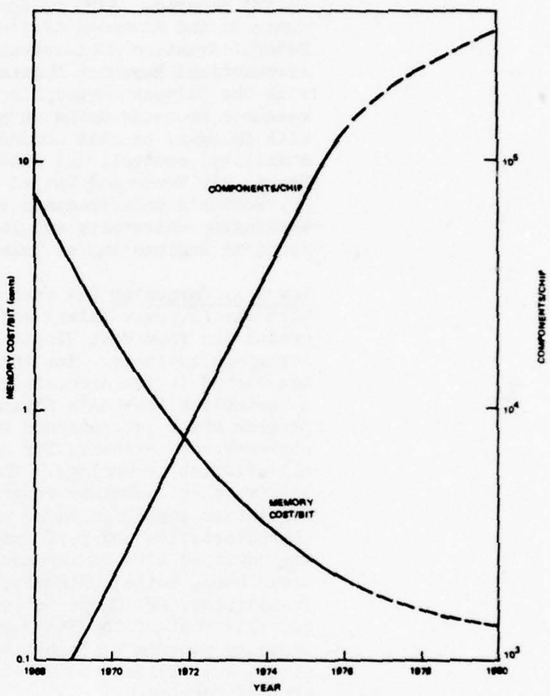

FIGURE 1. TRENDS IN ELECTRONICS - COMPONENT DENSITIES

The rapid pace of microcircuit and, hence, microprocessor development will significantly affect aircraft systems in two ways. On the low end,

the microprocessors that currently exist are getting less expensive. This trend will encourage the use of a much larger number of microprocessors in a typical system; e. g., they are likely to be embedded within sensors, actuators, displays, propulsion systems, etc. The use of microprocessors will increase the system's effectiveness and efficiency. On the high end, the microprocessors are getting more capable and will be able to take over the central flight control computer functions.

The advances in digital technology that are making the cost per function significantly less does not mean that the total system's costs are going down. It is most likely that the costs for total flight control electronics will stay constant or even rise. The big advantage will be the increased capabilities of the systems which can be used to develop more complex but extremely more efficient equipments to perform functions that had not previously been considered.

Therefore, some ACT functions are being applied to derivatives of current transport aircraft with additional functions, offering greater advantages, being considered for future designs.

Essentially, ACT implies aerodynamic control surfaces which are automatically actuated in an effort to satisfactorily provide handling and maneuverability characteristics, improved structural protection, and better passenger and crew comfort to an aircraft whose aerodynamics alone may be unable to do so (reference 4).

ACT in the near term, 1980 to 1985 time frame, principally consists of two concepts; i. e., relaxed static stability and wing load alleviation (WLA) to allow wing-tip modifications with minimum structural modification. Wing-tip modifications that would use actively controlled WLA for structural augmentation are extensions and/or winglets (small vertically-oriented surfaces mounted at the tips of the wing). Active controls would be employed to alleviate the increase in wing bending, torsion, and shear loads due to wing-tip modifications. Employment of the proposed tip modifications will increase the aircraft's lift-to-drag ratio which thus will improve performance.

Wing Load Alleviation (WLA) is a structural augmentation system designed to limit structural requirements when gross weight and wing span are increased. The primary purpose of a WLA system is to redistribute steady-state aerodynamic loads and alter cyclic loads. Currently, ACT systems comprising the WLA system are maneuver load control, gust load alleviation, elastic mode suppression, and flutter mode augmentation. Definitions for ACT are given in references 5, 6, 7, 8, and are briefly restated below:

a. Maneuver Load Control (MLC) is a system designed to redistribute the lift along the wing span from the tip towards the wing root (Figure 2 from references 3 and 4), thus reducing the bending moment as shown in Figure 3 from reference 9. MLC takes advantage of underutilized lifting capacity near the root while reducing the lift near the tips.

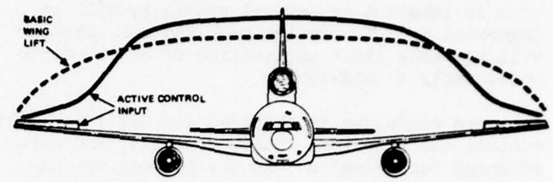

FIGURE 2. LOAD REDISTRIBUTION WITH ACTIVE CONTROLS

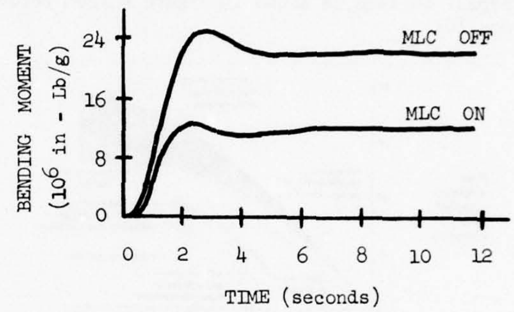

FIGURE 3. MANEUVER LOAD CONTROL EFFECT - WING ROOT

b. Gust Load Alleviation (GLA) is a technique to reduce peak transient loads on the structure that have resulted from atmospheric turbulence. The extent to which GLA is effective in performing its function can have a significant impact upon the aircraft's structural strength and fatigue requirements.

c. Elastic Mode Suppression (EMS) is a concept that is employed to damp fundamental structural bending mode oscillations that have been excited by a sudden dramatic atmospheric or aircraft-induced disturbance. EMS attempts to reduce the fatigue damage and aircraft inefficiencies which would result from the stress-level oscillations in the structure if cyclic loads were allowed to persist.

d. Flutter Mode Augmentation (FMA) is a load control technique that attempts to alter the apparent structural mass/stiffness or aerodynamic damping of the wing's flutter mode through use of automatic flight controls. The purpose for an FMA will be to work in concert with other WLA systems to increase the flutter margin of the aircraft structure.

Relaxed Static Stability (RSS) is potentially one of the major areas for maximum realization of benefits of ACT. Through a more aft center-of-gravity location, RSS allows for a smaller tail volume, decreased airframe weight, reduced drag, and thus, a more efficient aircraft. The reduction in inherent or natural stability will be augmented by ACT. Design problems and unknowns will probably limit application of RSS concepts until early to mid-1980.

Cautious evolution is expected for digital flight control and avionics, active controls, and other advanced technologies. As the systems are exposed to "real-world" flight time, confidence in the system's operational reliability will grow. Flight critical applications of advanced technology will then likely be exploited to the fullest extent possible. The potential fuel efficiency gain from advanced technology with respect to time is shown in Figure 4 from reference 10.

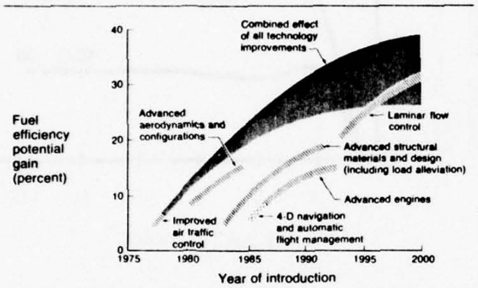

FIGURE 4. TECHNOLOGY IMPROVEMENT

As a Government stimulus to industry to encourage application of more efficient aircraft system concepts and capabilities, the United States Senate Committee on Aeronautical and Space Sciences suggested that the National Aeronautics and Space Administration (NASA), ". . . consider establishing a clearly defined goal of demonstrating the technology necessary to make possible a new generation of fuel-efficient aircraft." In response, NASA established a task force of Government scientists and engineers who served as a basis for the establishment of the NASA Aircraft Energy Efficient (ACEE) program (reference 1). The ACEE program is currently promoting advanced systems technology as one means of improving energy efficiency.

Simultaneous to NASA efforts, the FAA was completing a staff study on the background and potential impact of ACT (reference 5). Also, a joint NASA and FAA workshop (reference 11) was undertaken to investigate methods for certification of digital flight control and avionic systems. These activities indicated that the introduction of derivative aircraft using advanced systems would occur in the 1980 to 1983 time frame. A new generation aircraft which may be critically dependent upon systems concepts is expected in the mid-1980's.

Thus, the FAA will be confronted, in the near future, with the task of revising and modernizing its airworthiness standards and certification procedures to maintain flight safety for transport aircraft utilizing advanced systems technology. Present standards address certification from the concept of separate engineering disciplines. Aircraft incorporating advanced digital flight controls and avionics, active controls, and related concepts will be dependent on the interaction of the pilot, the control and augmentation system, the propulsion system, and the structure as a total integrated system. For the FAA to meet its responsibilities, concentrated effort must be initiated to acquire generic data and information to assure that airworthiness standards and certification procedures keep pace with the technology.

In anticipation of an impact on airworthiness standards and certification procedures, the FAA Flight Standards Service (AFS), Office of Systems Engineering Management (AEM), and Systems Research and Development Service (ARD) established the AIFS technology program in December 1976. The initiation of the AIFS technology program established an AIFS Planning Group staffed by personnel from the following FAA organizational functions:

a. Flight Standards Service

Engineering and Manufacturing Division
Air Carrier Division
General Aviation Division

b. Office of Systems Engineering Management

Advanced Concepts Staff

c. Systems Research and Development Service

Aircraft Safety and Noise Abatement Division

d. Office of Personnel and Training

Training Programs Division

The purpose of the Planning Group is to develop the required program tasks. This has been accomplished by the generation of an "Engineering and Development Program Plan - Advanced Integrated Flight Systems (AIFS)," Report Number FAA-ED-18-3 (reference 12) dated May 1978. This Plan has been incorporated into the Program 18, "Aircraft Safety, Engineering and Development Plan."

The FAA AIFS technology program objectives are:

1. To evaluate and assess advancing technology for impact on FAA.

2. To support the development of airworthiness standards and certification procedures.

3. Disseminate technical information within FAA.

Critical issues which relate to the airworthiness considerations and which must be addressed by the FAA are:

1. Systems failure modes and failure effects.

2. Hardware and software reliability, including verification and validation.

3. Lightning, electromagnetic, and other transient effects.

4. Aircraft flight characteristics and performance.

5. Structural aspects of active controls.

This program, to a large extent, is designed to monitor the activities of NASA (Langley, Ames, Lewis, and Dryden Centers), the Department of Defense (DOD) laboratories, and industry. Where necessary, FAA funded contracts or interagency agreements will be used to satisfy specific FAA requirements.

The AIFS technology program includes the following major project elements:

1. Airworthiness Standards and Certification Procedures.

2. Digital Flight Control and Avionics.

3. Flight Characteristics and Performance.

4. Structures.

5. Propulsion Control.

6. Crew.

7. Training.

PRODUCTS/EXPECTED RESULTS

The above seven elements will result in the acquisition of appropriate generic information, and the development of recommendations from which AFS may develop appropriate certification procedures or form a basis for revised airworthiness standards. The training element will transfer a part of the acquired information to the AFS regional personnel to aid in the certification process.

Detailed end item products/results relate to:

- Identification of affected Federal Aviation Regulations (FARs).

- Development of background, rationale, and justification for:

  - Revised certification procedures and methods for advanced systems.

  - Guidance criteria to FAA and industry.

- Transfer of data to FAA training channels.

The major project elements discussed below involve various technical disciplines within the FAA organizational structure. The task(s) delineated within each project element (per the Engineering and Development Plan) are efforts which, in the FAA's opinion, need research to meet certification requirements.

1. Airworthiness Standards and Certification Procedures for AIFS. This project is directed toward the determination, validation, and development (as required) of airworthiness standards and certification procedures for both near-term derivative aircraft and far-term new generation aircraft. In addition to being the lead project by establishing the need for work to be accomplished, this project will assimilate the results of AIFS program efforts directed towards the revision of airworthiness standards and certification procedures.

2. Digital Flight Control and Avionics. Digital flight control and avionics are the most defined areas with a considerable amount of activity already begun and more planned for the near future. With advanced digital technology features and capabilities, indications are that digital avionics systems will almost certainly continue to be put into wider flight control applications. As such, the failure (error or fault) and redundancy management characteristics must be thoroughly understood. While absolute safety is an unattainable ideal, the risk of a catastrophic event must be minimized. This requires evaluation of the risks associated with the following factors:

- Software and hardware validation and verification.

- Failure modes and effects.

- Fault detection and isolation.

- Lightning transient and electromagnetic interference effects.

3. Flight Characteristics and Performance. Incorporation of advanced systems will provide improved aircraft handling qualities during normal operating modes. However, with system failures or cascading multiple failures, degradations in both handling qualities and performance may occur. Safety implications associated with systems failures suggests consideration of several developmental projects; i. e., minimum safe flying qualities, failure identification, demonstration of failures, simulation, etc.

4. Structures. Advances in ACT have demonstrated a potential application for the simultaneous control of rigid body and structural motion to alleviate aircraft structural stresses. Near-term

ACT functions for derivative airplanes are being considered mainly to avoid or reduce wing structural beef-up normally needed when increasing the maximum design weights and/or adding wing-tip extensions/winglets. In the long-term, the maximum potential of ACT when applied as an integral part of new aircraft design is subject to, as of yet, unknown design constraints. However, such aircraft will rely on active control concepts in flight-critical applications.

The impact by these advanced concepts on the structural integrity of the aircraft impose several airworthiness concerns; e. g., bending moments, shear, and torsional loading of the wing, flutter, buffeting, etc. The AIFS program will develop the guidance criteria required for structural certification of advanced flight controls.

5. Propulsion Control. Advanced digital technology will provide a feasible means for integrating the propulsion control system with the aircraft flight control system and for continuously matching the engine operating point with the aircraft state and flight conditions. A number of sensor inputs from the air data source and from the aircraft state measurements, in addition to sensed measurements of propulsion system state, will have to be appropriately integrated to achieve maximum fuel efficiency and minimum installed drag. In fact, full digital electronic control systems may be essential because of the projected wide use of variable geometry and the large number of variables to be controlled in future engines. Control configured aircraft with variable geometry engines will utilize interactive airframe and thrust effects by design, and such effects must be considered from the onset of the synthesis process. The AIFS program will develop guidance criteria for certification of an actively controlled and integrated propulsion system.

6. Crew. The AIFS program will investigate and identify the necessary flight safety criteria needed for evaluating human engineering practices and training principles on advanced integrated flight systems. The necessary research to be done concerning the crew's impact from AIFS will include the determination of the flight safety impact of the crew-machine interfaces as related to advanced flight controls and avionic technology, and to identify requirements and establish training criteria for advanced technology aircraft whereby handling characteristics may be different from current fleet stability and control operating modes.

7. Training. Training of AFS regional and technical and operational personnel on the AIFS technology program products is considered a primary program goal. Program workshops and technical training that is a result of the research conducted (in accordance with the planning document) will be conducted as the need occurs.

TECHNICAL APPROACH

Project element milestones and events are keyed to the introduction of derivative aircraft expected in the 1980 to 1983 time frame with the new generation aircraft expected post-1985.

The task(s) delineated within each project element are efforts which, in the FAA's opinion, need research to meet certification requirements. The research may be accomplished by:

- Monitoring and coordination of ongoing work in NASA, DOD, and industry.
- Joint project funding with NASA and DOD.
- FAA funded contracts.
- FAA in-house efforts.
- Government and industry workshops.

Interagency cooperative efforts include the NASA/ACEE Energy Efficient Transport (EET) programs at Langley Research Center (LaRC) and those conducted by the Electronics Directorate at LaRC addressing advanced digital systems technology. The Ames Research Center (ARC) is supporting program elements in digital flight controls and avionics systems using their simulation capabilities. Related programs at the NASA-Lewis Research Center (LeRC) and Dryden Flight Research Center (DFRC) will also provide data and information. The Air Force Flight Dynamics Laboratory (AFFDL) and Aeronautical Systems Division (ASD) are additional interfaces.

In the following paragraphs, current projects for respective elements are described. These are projects which the FAA has funded (for interagency agreements or contracts) plus in-house activities. Some elements do not have work currently underway but are in the early procurement phase.

AIRWORTHINESS STANDARDS AND CERTIFICATION PROCEDURES

- FAR Impact Study. An in-house study was performed to determine the impact advanced integrated flight systems technology will have on the FARs. This was the lead project for the AIFS Planning Group and it forced the Group to realistically identify the FAA's real needs; i.e., guidance criteria for certification procedures. The conclusion drawn from this study was that near-term derivative technology applications would probably only require that general guidance criteria be formulated. Therefore, for the near-term, minimum impact to the FARs is anticipated.

  - Objective: Determine impact of advanced technology on FARs.

- Requirement: Paragraph 3.1.1, Engineering and Development Program Plan/AIFS (Report Number FAA-ED-18-3).

- Milestones:

Project Initiated	October 1977
Project Complete	December 1977

- Approach: In-House.

• Guidance Criteria Study. As a result of the first in-house study, a second study was initiated to develop an approach and to formulate guidance criteria for certification procedures. A brief was prepared to define the function and configuration of advanced technology as it will exist and perform in the near-term 1980 to 1983 time frame. Guidance criteria to FAA regional offices in some form is expected to be available in late 1978/early 1979. This schedule should still afford industry an early time frame benefit of FAA's unified position.

- Objective: Develop FAA regional guidance criteria for AIFS.

- Requirement: Paragraph 3.1.1, Engineering and Development Program Plan/AIFS (Report Number FAA-ED-18-3).

- Milestones:

Project Initiated	January 1978
Preliminary Assessment	March/April 1978
FAA/Headquarters/ Regional Workshop	July/August 1978
Strawman Draft of Guidance Criteria	August 1978
FAA/Industry Workshop	October/ November 1978
Guidance Criteria to Regions	December 1978

- Approach: In-house.

DIGITAL FLIGHT CONTROL AND AVIONICS

• Simulation Methods for Advanced Digital Flight Control and Avionic Systems. This NASA-ARC/FAA project is an outgrowth of the digital flight controls and avionics workshop conducted in April 1976. This task will investigate the role of real time simulation in the verification of the failure mode and effect analysis for digital flight controls and avionics; improve acceptance of advanced concepts by identifying the potential of validation processes and simulations; define the impact of failures, intermittents, faults, errors, etc., in digital systems on safety of flight aspects and the role of the pilot through simulation concepts; and recommend methods and procedures that may be used in validation; i. e., analysis, simulation, flight test, or combinations.

- Objective: Assess the potential of simulation methods for the validation of failure modes/effects analysis of digital flight control and avionic systems.

- Requirement: Paragraph 3.2.1, Engineering and Development Program Plan/AIFS (Report Number FAA-ED-18-3).

- Milestones:

Phase I, Study Phase — December 1978

Define AIFS configuration for simulation. Recommend simulation experiments. Investigate software concepts.

Phase II, Review, Assessment, Development, and Validation of Reliability Prediction Software — October 1979

Review, selection, development, and validation.

Reliability and failure effects criteria.

Phase III, Methods for Validation of Flight Software — November 1979

Review, assess, and describe various validation concepts.

Describe documentation concepts.

Phase IV, Conduct Systems/Mission Simulation Investigations — December 1981

Investigate advanced hardware/software concepts, non-piloted and piloted.

Industry/Government Workshops — June 1978, December 1979 and 1981

- Approach: Interagency Agreement with NASA/ARC and funding transfer.

• FAA/NASA-DFRC Workshop. The NASA-DFRC and Draper Laboratory presented to the FAA the experience acquired during the program planning, implementation, validation, flight qualification, and testing of the NASA digital fly-by-wire flight control systems aircraft. This program experience is considered invaluable as background information to the FAA in the civil certification of derivative and new generation aircraft.

- Objective: To disseminate in a timely manner information of a generic value which may be useful to the FAA in formulating guidance material and methods for advanced systems certification.

- Requirement: Paragraph 3.2.1, Engineering and Development Program Plan/AIFS (Report Number FAA-ED-18-3).

- Milestones:

NASA-DFRC Workshop	June 20-22, 1978
NASA-DFRC Report	June 1978

- Approach: Reference Interagency Agreement above.

• NASA-ARC, Phase I Contractor(s) Workshop. The NASA-ARC program (see Simulation Methods above) has three contractors; two for CTOL and one for helicopters, which will participate in the Phase I study efforts.

- Objective: The Phase I effort will obtain in-depth industry perspective relative to experience in methods (analysis, simulation, flight) for the validation and failure effects analysis of digital flight control and avionics. Identification of those potential digital flight control and avionics candidates for pre- and post-1985 will be included.

- Requirement: Paragraph 3.2.1, Engineering and Development Program Plan/AIFS (Report Number FAA-ED-18-3).

- Milestones:

Workshops at NASA-ARC (3 contractors)	December 1978
Workshops at ASO, ANE, AWE Regions	January - February 1979

- Approach: Reference Interagency Agreement above.

• Lightning and Static Discharge Effects. With the advent of low-voltage and current function solid state components and devices which are being used in new generation digital flight control and avionic systems, there are increasing concerns relative to electromagnetic interference effects. The impact of lightning or static discharge effects on flight-critical systems are almost unknown. Earlier vacuum tube electronics and even solid state analog devices were less susceptible to lightning-induced surges. However, solid state microcircuitry is more vulnerable to disability or upset due to lightning or other transient effects. The indirect effects have been receiving increased attention as new generation aircraft operation will be dependent on highly complex electronic systems. Nonmetallic composite structures may accentuate these problems. With digital flight control and avionics, the indirect effects of lightning or other static discharge sources are likely a hazard to safety of flight.

- Objective: To determine lightning and static discharge effects upon advanced digital flight control and avionic systems.

- Requirement: Paragaph 3.2.7, Engineering and Development Program Plan/AIFS (Report Number FAA-ED-18-3).

- Milestones:

Lightning Study Flight Test Program	May 1978
Based on NASA/USAF Flight Tests and SAE studies, conduct test measurement studies and experimentation	January 1979
Investigate the indirect effects by analysis, simulation, and flight test on digital flight control and avionic systems	July 1979
Analysis of results of above efforts	January 1980

- Approach: Interagency Agreement with NASA-LaRC and funding transfer.

• Hardware and Software Functional Assessment Concepts. This project is to provide research for the functional assessment of advanced computer and software architecture schemes and the investigation of diagnostic emulator concepts. Attempts will be made to explore and acquire an understanding and to develop methods to prove that system designs meet their functional performance specification(s). Research will be conducted to develop the capabilities (i. e., mathematically-based methodoligies, etc.) to assess the functional operation of advanced computer and software concepts to fulfill the needs of flight control and avionic system applications and to investigate possible diagnostic emulator concepts for analyzing the performance and behavior of hardware and software designs. A selected concept may be developed and implemented for experimental research. Appropriate recommendations and documentation shall be provided for civil application.

- Objective: Develop a mathematically-based methodology whereby the design of any digital computer or computer system abstractly stated in a formal specification language can be proven to achieve the specification or design intent. Also, develop a diagnostic emulator for analyzing the performance and behavior, in the presence of faults, of hardware and software designs without the need for physical implementation of the hardware.

- Requirement: Paragraph 3.2.5, Engineering and Development Program Plan/AIFS (Report Number FAA-ED-18-3).

- Milestones:

Assessment of mathematical design proof methodologies	October 1978
Review and assessment of diagnostic emulator	October 1981

- Approach: Interagency Agreement with NASA-LaRC and funding transfer.

FLIGHT CHARACTERISTICS AND PERFORMANCE

• Simulation Validation in Aircraft Certification. As aircraft system complexity increases, the associated testing and failure testing of these systems in flight may present unacceptable hazards. Therefore, the use of simulation becomes an obvious means for efficiently and safely aiding the certification process. In anticipation of this need by industry to use simulation for certification compliance credit, the FAA desires to obtain the knowledge by which it can develop guidelines to assure the quality and fidelity of a simulator.

Advisory Circular (AC) 21-14, dated June 12, 1975, presented the FAA's views on using simulation in certification (e. g., open or closed loop mathematical models, man-in-the-loop, etc.). As a follow-on to AC 21-14, a study entitled "The Role of Simulation Methods in the Aircraft Certification Process," Report Number FAA-RD-77-17 dated March 1977, provided an assessment of potential areas where simulation could be used in the certification process. The current effort will be a two-phase program to acquire a knowledge base that would aid in establishing guidelines for assuring the validity of simulation data when used for certification compliance credit.

- Objective: Develop generic data for validating simulation from which aircraft certification guidelines can be formulated.

- Requirement: Paragraph 3.3.3, Engineering and Development Program Plan/AIFS Report Number FAA-ED-18-3.

- Milestones:

Procurement Request developed	May 1978
Request for Proposals	August - September 1978
Contract Award	February 1979
Phase I Workshop (critique plans)	December 1979
Phase II Workshop (critique results)	October 1980
Final Report	December 1980

- Approach: Competitive Procurement.

STRUCTURES

• Aircraft Certification Procedures for Structural Loading. By 1980/1981, airframe manufacturers plan to certify derivative aircraft that will incorporate energy efficient concepts and devices, one such system being WLA. The systems will employ active controls and digital avionics to modify the wing's aerodynamic loading, allowing the structural design to be relaxed. Technically, the benefits are good; less structural weight connotes a more efficient aircraft. However, the system complexity and dependency is increased, thus creating concerns in airworthiness criteria and flight safety.

The current effort will seek to obtain proprietary methodologies and techniques from which acceptable means of compliance for structural loading certification will be developed for systems when considering active controls. The FAA's objective is to obtain demonstrated procedures for calculating bending moments, torsion, and shear loads resulting from the aircraft's response to turbulence, including methods for combining these components. The procedure is to be arranged in a manner so as to be available and usable by smaller airframe manufacturers possessing modest computational equipment and is to be correlated with flight data, fully described, and documented.

- Objective: Obtain methodologies for combining and calculating bending moments, torsion, and shear loads resulting from an aircraft's response to turbulence.

- Requirement: Paragraph 3.4.1, Engineering and Development Program Plan/AIFS (Report Number FAA-ED-18-3).

- Milestones:

Procurement Request completed	February 1978
Request for Proposals	June 1978
Contract(s) Award	September 1978
Final Report(s)	July 1979

- Approach: Competitive Procurement.

• Aircraft Structural Loads Criteria based on Aircraft and Atmospheric Dynamics. Future aircraft employing augmented stability may have its

flight loads uniquely influenced by interactions between the pilot and the total system. This project is reevaluating the loads estimation techniques to develop data on structural flight loads, with emphasis on continuous atmospheric turbulence, turbulence penetration speeds, and the effects of aircraft and control system dynamics. The effects of aircraft stability, control, and handling qualities and the influence of turbulence with the pilot-in-the-loop are being considered.

- Objective: Evaluate effects of aircraft and atmospheric dynamics on aircraft structural loads criteria.

- Requirement: Paragraph 3.4.3, Engineering and Development Program Plan/AIFS (Report Number FAA-ED-18-3).

- Milestones:

Reevaluate Loads estimation techniques	August 1977
Identify Specific accidents	January 1978
Accident File Analysis	July 1978
Contract complete	August 1978

- Approach: Competitive Procurement awarded in January 1977 to Systems Technology, Incorporated

SUMMARY

The incorporation of advanced technologies into derivative transports and future new transport designs connotes safety implications and industry and Government responsibilities. It is impossible to guarantee absolute safety, but it is essential to minimize the risks. Since digital flight control and ACT systems are expected to be "flight-critical," reliability no less than that of traditional passive systems would be expected. We in the FAA recognize that advanced digital flight control and active control technology will be integrated into designs of the future, and in our role, we intend to be responsive to industry. The FAA has made the initial step to understand this technology by establishing the AIFS technology program and establishing an AIFS Planning Group to develop and implement the program.

Commercial aviation is apparently entering another technology era, with impact similar to that of the jet transport age. From the point of view of advanced integrated flight system concepts, there are many unknowns and few certainties regarding certification of the systems. While increased emphasis is being placed on improving performance, fuel efficiency, and productivity in air transportation, priority will continue to be given maintaining a safety record unparalleled by any other transportation mode.

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RESEARCH AND DEVELOPMENT OF ANTIMISTING KEROSENE (AMK) FOR REDUCTION OF THE POST-CRASH FIRE HAZARD

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Biographies

Mr. Van Dyke joined the Federal Aviation Administration in 1969, and has served as Mathematical Statistician in several divisions in the Systems Research and Development Service. For the past year, he has served as a Program Manager in the modified fuel area. He received the M. A. degree in mathematics at Michigan State University in 1956, where he served on the faculty until 1960. From 1960-1963, he was a Mathematical Statistician at the National Bureau of Standards, and from 1963-1969 in the same capacity at the Food and Drug Administration.

Mr. Horeff was employed in 1948 by McDonnell Aircraft as a Flight Test Data Analyst and then served with the Army from 1951-1953 as a Gasdynamicist in ramjet development at Redstone Arsenal. From 1953-1957, he was with Curtiss-Wright where he was an Assistant Project Engineer in advanced ramjet development. He started with the FAA in 1957 serving first in the New York Office as a Power Plant Installations Design Evaluation Engineer; then in the Atlanta Office as a Propulsion Staff Engineer; and now in the Washington Office where he was Propulsion Program Manager in SRDS until 1977, when he assumed his current position as Chief of the Propulsion Branch in Flight Standards Service.

ABSTRACT

This paper describes the status of research programs in the United States and the United Kingdom to minimize fuel mist formation during an aircraft crash. The concept concerns fuel modification so that a coarse spray is created which will inhibit ignition and flame propagation, thereby decreasing the probability and severity of fire following a survivable accident and providing for improved conditions for safe occupant evacuation. Successful preliminary tests have lead to a program to check the usefulness of the fuel additive in large-scale crash tests and to check the effect of the additive on the fuel system.

BACKGROUND

Impact-survivable accidents have occurred during approach, landing, and takeoff where fuel was released from severed wings or damaged fuel tanks, resulting in external fires and thermal fatalities. The fuel released under such conditions forms a fine mist of combustible vapor which is readily ignited, resulting in a fire which could envelop the aircraft and serve as a major ignition source for continuing fuel spillage as the aircraft comes to rest.

Fuel was released from separated wings in 17 impact-survivable U. S. air carrier turbine aircraft fatal accidents from 1964 through 1976 and from damaged tanks in eight fatal accidents, resulting in external fires and an estimated 360 fatalities due to fire or its effects. These 25 wing separation and tank damage fire accidents represent 78 percent of the total 32 survivable/fatal accidents (33 percent of the total 75 fatal accidents) and the estimated 360 fatalities due to fire in these accidents represent 32 percent of the total survivable accident fatalities (14 percent of the total fatal accident fatalities). Since antimisting fuel is intended to inhibit ignition and flame propagation when fuel is released during wing separation and tank damage accidents, it is possible to speculate, based upon this accident experience, that up to 32 percent of the fatalities in impact-survivable accidents might have been prevented by the use of antimisting fuel.

The initial objective of the FAA program was to develop a modified fuel which could be used in routine flight operations and also be capable during a survivable crash of (1) restricting spillage from ruptured tanks and reducing the area of spills on the ground; (2) decreasing the probability of ignition and rate of horizontal flame propagation; and (3) eliminating the mist of combustible vapor which is produced by fuel released under dynamic conditions. The first contractual effort was completed in 1966 and produced a thick semi-solid gelled fuel

employing 1.5 percent by weight N-Coco - γ - hydroxybutyramide (CHBA) which exhibited good fire control characteristics in these three areas due to its ability to physically bind the fuel and reduce the rate of vaporization and the exposed surface area available to support a fire (Ref. 1). This highly viscous gelled fuel could not be used in routine operations since engine and aircraft fuel system and ground refueling system compatibility problems were severe (Ref. 2).

A follow-on contractual effort in 1967 to develop a gelled fuel which had comparable fire reduction characteristics and better system compatibility characteristics resulted in an aluminum octoate gel (Ref. 3) which was not an acceptable candidate (Ref. 4). Samples of emulsified fuels and independently developed less-viscous gelled fuels were also submitted to FAA in 1967 and 1968 for evaluation of their relative static and dynamic crash fire characteristics in small-scale tests (Ref. 5 and 11).

An emulsified fuel having a yield stress of 700 dynes per square centimeter and two percent sodium-free styrene polymer gelled fuel in the 13,000 - 15,000 centipoise viscosity range with a yield stress of 400 dynes per square centimeter showed good fire reduction characteristics in these tests and were selected in 1968 as the fuels to be used in jet transport fuel system compatibility tests.

These tests indicated that the gelled fuel was more compatible with the fuel system compared to the emulsified fuel but that extensive fuel system modifications were required to compensate for the high viscosity of the gelled fuel and to enable system performance to approach that with conventional fuel (Ref. 6). If this gelled fuel were to be used in commercial airline operations, it was estimated that airline total operating costs would be increased by 4.5 percent for the first 10-year period, primarily due to the fuel additive and system modification costs (Ref. 7).

The continuing in-house developments by the Dow Chemical Company and Anheuser-Busch, Inc., of gelled fuel candidates having lower viscosities in the 5,000 centipoise viscosity range with zero yield stress and good fire reduction properties resulted in the award of contracts in 1970 to these two companies to optimize these gels from the viewpoint of minimum viscosity consistent with crash fire reduction. The Dow effort produced a 1.7 percent hydrocarbon resin "gelled" fuel with a viscosity range of 250 to 550 centipoises and zero yield stress at 75°F, which is about 97 percent less viscous than the gel used in the fuel system compatibility study (Ref. 8). The Anheuser-Busch carbohydrate resin fuel had similar characteristics (Ref. 9).

The lower viscosity of these fuels offered promise of reducing the estimated 4.5 percent increase in total operating costs to less than a 2.0 percent increase if major system modifications were not required. A 26-hour J-79 engine ground test and CV-880 aircraft fuel system ground test were completed in 1971 using the Dow fuel. These tests indicated that fuel system unusable fuel quantities were comparable to those with conventional fuel and that engine fuel nozzles should be modified for proper operation during starting low RPM operation.

A contractual effort to improve fuel nozzle performance was initiated but was held in abeyance due to the advent in late 1971 and early 1972 of new "antimisting" fuels employing 0.2-0.7 percent of high-molecular-weight polymeric additives with viscosities about double that of conventional fuel at 75°F. Preliminary testing of these "antimisting" modified fuels indicated that their fuel mist fire suppression characteristics were comparable to those of the earlier more viscous gelled fuels and that they should have less system compatibility problems than the gelled fuels at the expense of less restriction of fuel spillage. These fuels confirm the trend which became apparent in 1970 that the fire suppression characteristics of modified fuels are not dependent on viscosity (Ref. 10).

The FAA program was redirected in mid-1972 toward consideration of these new modified fuels in coordination with military and British programs. It should be emphasized that previous testing (Ref. 5 and 11) has indicated that the various additives which have been developed do not have as great an effect on reduction of the fire characteristics of JP-4 as compared to kerosene because the lower flash point and higher volatility rate of JP-4 have a greater influence on fire properties than the additive composition. The antimisting fuel program will continue to evaluate only the modification of kerosene fuel.

Five antimisting additives have been evaluated by U. S. and British agencies; AM-1 developed by Continental Oil Co., XD-8132 by Dow Chemical Co., PEP-4 by Shell Development Co., and FM-4 and FM-9 by Imperial Chemical Industries, Ltd., under British Government contract. FM-4 was superseded in the British program by the polymeric additive, FM-9, which became available for testing by U. S. agencies in 1976. Since initial testing of FM-9 has given results surpassing those of other additives, the FAA's recent research has been confined to its acceptability.

PRODUCTS EXPECTED

The expected products from the planned antimisting kerosene program are:

1. Data base that provides proof of the concept that antimisting fuel additives are a viable product for improving occupant survivability in impact survivable accidents.

2. Documentation of research test data that establishes the aircraft operational feasibility of antimisting kerosene fuel for commercial turbojet aircraft.

3. Documentation of studies which demonstrate the feasibility of meeting production and logistical requirements for antimisting kerosene as a world-wide fleet fuel.

4. Documentation of results from studies that examine the costs associated with the introduction of antimisting kerosene into world-wide commercial fleet operation.

5. In summary, data that would provide proof of concept of antimisting kerosene fuel sufficiently to support FAA regulatory action.

TECHNICAL APPROACH

U. S. SMALL-SCALE FLAMMABILITY TESTS

The mist flammability characteristics of these antimisting kerosenes were initially investigated in the United States by (1) the air gun test method which was used to evaluate the earlier gelled fuels; (2) the catapult test method; (3) the mist-flashback test method designed by the Army Fuel and Lubricants Research Laboratory; and (4) the simulated helicopter impact test. In the air gun test method, a 1-gallon container of AMK is propelled horizontally by the air gun at velocities up to 130 knots against a steel screen which causes the fuel to disperse over open flames or other ignition sources located downstream of the screen. The ability to resist ignition or the percentage of reduction in the size of the resultant fire compared to the size of the fireball produced by conventional fuel is measured visually and used for rating the fire reduction effectiveness of candidate fuels (Ref. 11). A larger-scale assessment is provided by the catapult test method where a 20-gallon container of AMK is propelled by the catapult and released along the ground at a velocity of 70 knots against a 45-degree steel incline which causes the fuel to disperse over open flames downstream of the incline. In the mist flashback apparatus, three intersecting air streams impinge upon the AMK issuing at a steady flow rate from the tip of a capillary tube causing the fuel stream to break up into a spray. A pilot flame is positioned perpendicular to the fuel-air jet 12 inches downstream from the air impingement point. The spray is ignited as it passes through the pilot flame, and the distance of flame propagation upstream from the pilot flame toward the fuel-air source, or "flashback," is measured. No significant differences in mist flammability properties for AM-1, FM-4, and PEP-4 at the 0.3 percent concentration level were determined by this technique, while the mist flashback level for XD-8132 was slightly greater at concentrations up to 0.7 percent (Ref. 13).

The simulated helicopter impact test indicated that 0.2 percent AM-1, 0.3 percent FM-4, and 0.7 percent XD-8132 had good mist fire safety characteristics under survivable helicopter crash conditions. In this test, a 13-gallon simulated helicopter fuel tank containing AMK is mounted on a sled fixture and accelerated to 39 knots on a monorail system into an impact barrier located adjacent to the monorail. The face of the barrier is concrete at a 45-degree incline and is fitted with two steel tank cutters to insure fuel bladder rupture which could take place in an actual crash on rough terrain. The fuel is dispersed over ignition sources (spark igniter, hot surface igniter, or open flames) and fire reduction effectiveness is recorded by high-speed photography (Ref. 12).

The development of a small-scale test configuration for evaluative comparison of the flammability of modified fuel sprays was carried out at FAA's National Aviation Facilities Experimental Center (Ref. 18). The configuration consisted of a 1/4-inch fuel delivery tube within a 1-inch air atomization pipe followed by a deceleration cone. Photographic evaluation required design of a unique fuel spray photographic chamber which had the capability of photomicrographic, schlieren, and stroboscopic photographic techniques. The chamber employed positive pressurization with diluent air to prevent spray recirculation and fuel deposition on optical components. The spark photographs proved that the breakup phenonomen could be scaled down without obliteration of the dominant rheological effects. Motion pictures of ignition showed the same flammability behavior shown in larger scale tests. It was concluded that the concentric tube atomization technique provided a practical method for evaluating modified fuels on a small scale.

U.K. SMALL-SCALE FLAMMABILITY TESTS

The Royal Aircraft Establishment (RAE) at Farnborough started work on antimisting fuel in 1967, using two tests to assess flammability characteristics; a minitrack test and a rocket

sled test. The minitrack system consists bascially of a propulsion unit capable of accelerating a small trolley up to a speed of about 72 knots, coupled to a braking system able to stop the trolley at a mean deceleration of about 30 g. The fuel tank has a 5/16 of an inch diameter orifice and nozzle on the front surface. At the beginning of each experiment the fuel tank orifice is closed with a weighted rubber bung. The deceleration when the trolley enters the braking system causes the bung to be ejected, thereby exposing an orifice through which fuel is ejected onto an array of ignition sources (Ref. 14).

The minitrack test is used to provide an indication of the additive concentration required to pass the rocket sled test. The rocket sled test consists of a fuel tank mounted on a rocket-propelled sled which is accleerated down a track into an aircraft arrester wire. The tank has a slit in its leading edge which, in the "standard" test, is closed by a weighted rubber bung. On contact with the arrester wire this bung is ejected virtually instantaneously and fuel is release through the slit so produced. The fuel is ejected onto an array of ignition sources, each consisting of a wick burning in a pint tin partially filled with kerosene. Two tanks have been used having capacities of 10 to 20 gallons. With the larger tank, the slit can be varied, the length being kept constant at 30 inches, while the width is varied from 0.125 inches to 1.0 inch. The smaller tank has a slit measuring 18 inches x 0.5 inches.

The tank velocity can be varied over a wide range by changing the number of rockets on the sled, by adding weights to the sled, or by altering the position from which the sled is fired. In practice, however, all runs in the "standard" test have started from one of two firing points, depending on whether one or two rockets were used.

A second type of test has been developed in which the exit velocity is considerably lower. In this "run on" test the bung is pulled out of the slit immediately as the rocket is fired. While the rocket motor continues to burn, the acceleration of the sled prevents fuel from emerging, since the slit is on the leading edge. Once the rocket ceases firing, friction decelerates the sled (0.5 g according to the sled speed) and fuel is ejected from the tank which is allowed to run past a series of ignition sources mounted above the center of the track. This test is aimed to simulate certain types of aircraft crash where impact forces are low; moreover, it provides information on the behavior of fuels under conditions where exit velocities are very low and thus where the amount of shear occurring on the edge of the slit is negligible (Ref. 15).

FAA FULL-SCALE AIRCRAFT FLAMMABILITY TESTS

The antimisting performance of modified fuel following s survivable crash was demonstrated in three actual full-scale crash tests of surplus Navy A-3 and Air Force RB-66 aircraft. (Ref. 19). These tests were conducted at the Naval Air Test Facility, Lakehurst, N. J., under FAA sponsorship and also served to indicate whether the small-scale air gun and catapult flammability test conditions are representative of conditions imposed on fuel released in an actual crash.

The A-3 and RB-66 are two-engine, swept-wing aircraft with a 750-gallon integral fuel tank in each wing and were selected for the crash test program because the engine pod and pylon arrangement and integral fuel tank configuration are representative of commercial jet transport aircraft. The first modified fuel crash test was conducted on September 1, 1972, using an A-3 airplane with 750 gallons of 0.3 percent AM-1 modified fuel in the left wing tank and 750 gallons of 0.3 percent FM-4 in the right wing tank. The engines were inoperative and no auxiliary external ignition sources were used for this test, since its primary purposes were to check the suitability of the test conditions and to determine the dispersion pattern of modified fuel. The airplane was propelled at 108 knots down a mile-long track by a jet cart against four poles which ruptured the wing tanks. A minimum of misting of the modified fuel was observed as the airplane then impacted a three-degree embankment and continued over the crest of this slope until it stopped just over the crest of a 15-degree embankment about 300 feet down-course from the poles. With the airplane at rest, it was noted that the remaining modified fuel spilled from the ruptured tanks in random sheet form and fell lazily to the ground. No fire occurred and the test impact conditions were considered to be survivable.

The second modified fuel crash test was conducted on October 20, 1972, at an outside air temperature of 50°F, using an RB-66 airplane with inoperative engines and with 1,500 gallons of 0.7 percent XD-8132 modified fuel in the wing tanks at 61°F. Following impact with four poles at 105 knots, the modified fuel was released from the ruptured areas of the wing tanks as the airplane impacted the three-degree embankment where railroad flares were suspended above and below and in line with each damaged area and continued to skid through an array of 40 additional railroad flares extending about 1 foot above the ground along the path of the airplane until it came to rest at the creast of the 15-degree embankment. The modified fuel was not ignited by these auxiliary external ignition

sources. The modified fuel in the damaged wing areas outboard the engines was then manually ignited and small fires were started which did not propagate as the fuel fell to the ground. These fires self-extinguished after several minutes.

The objective of the third crash test was to evaluate the performance of modified fuel in an abnormally severe ignition environment. This test was conducted on January 24, 1973, at an outside air temperature of 40°F using an RB-66 with 1,500 gallons of 0.5 percent XD-8132 modified fuel at 80°F and both engines operating on the modified fuel at 72 percent rpm. The ignition environment was more severe than in the second test due to four propane torch flames about 4 feet high at the crest of the three-degree embankment in line with the damaged wing areas and replacement of the railroad flares with 40 burning fuel-soaked waste filters located in eight rows of fives every 100 feet along the crash path and elevated at 4 feet above the ground. More fuel was released than in the second test because impact with the poles at 102.4 knots drove I-beam devices into partially drilled out areas in the front spar to increase the opened area at the leading edge and four access plates on the wing undersurface were removed just prior to impact with the poles.

The relatively massive and concentrated quantities of released modified fuel were initially ignited in the vicinity of the right engine prior to contacting the propane flames, creating a fireball which continued as the airplane skidded to a stop on level terrain.

Since 0.5 percent XD-8132 passed the small-scale air gun and catapult tests in a propane torch ignition environment at a fuel temperature of 95°F, it was apparent from the last crash test that the small-scale test conditions are not representative of full-scale crash conditions.

FAA LARGE-SCALE FLAMMABILITY TESTS

A new large-scale fuel spillage air shear test was developed which is more representative of full-scale crash conditions. In this test, a quantity of AMK up to 200 gallons is released from the leading edge of a simulated wing section into an airstream of 100-170 knots and an ignition environment of propane torches at varying locations with respect to the wing section. This test is used to establish the interrelationship between fire reduction effectiveness and additive concentration, fuel temperature, fuel quantity released, fuel condition (pumped or nonpumped), airflow velocity, and location and magnitude of ignition sources.

Results of tests conducted to date on FM-4 and XD-8132 at elevated fuel temperatures confirm the failure of 0.5 percent XD-8132 in the last RB-66 crash test and indicate that 0.3 percent FM-4 might also have failed. The test results further indicate that XD-8132 at a concentration of 0.7 percent as in the second crash test would probably have passed the last crash test at a fuel temperature of 95°F. XD-8132 at a concentration of 0.7 percent and 95°F fuel temperature also passed the United Kingdom rocket sled test with a propane torch added to the ignition array.

Figures 1-4 show components and schematics of the fuel spillage/air shear test facility at the Naval Weapons Center, China Lake, California. Recent use of this facility was primarily for the testing of the fire resistance afforded by additive FM-9 (Ref. 20). For these tests, additive concentrations varied from 0.3 to 0.5 percent and airstream velocities ranged from 100 to 170 knots. Fuel and airstream temperatures were held at approximately 80° and 90°F respectively. Fuel volumes released were 50, 100 and 150 gallons with average dump rates of 10-20 gallons/second. Figure 5 shows the fire (marginal/fail) - no fire (pass) envelope according to FM-9 concentration and air flow velocity. (Numbers at test points are test identifiers).

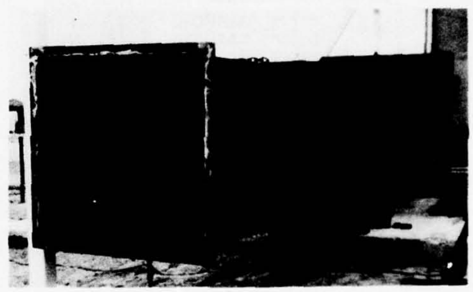

Figure 1. Low Velocity Air Diffuser

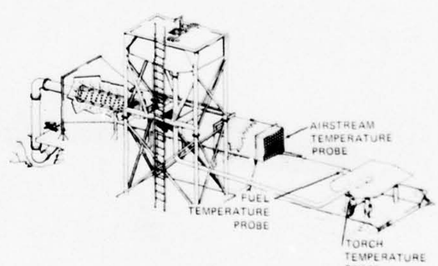

Figure 2. T-Range Low Velocity Flow Facility With Airfoil in Place

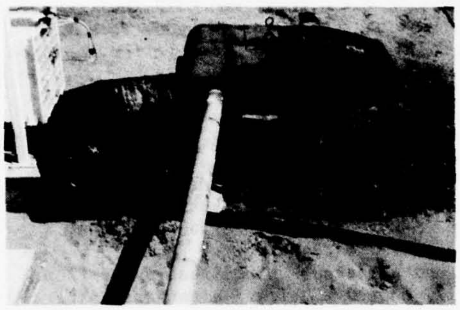

Figure 3. Test Airfoil

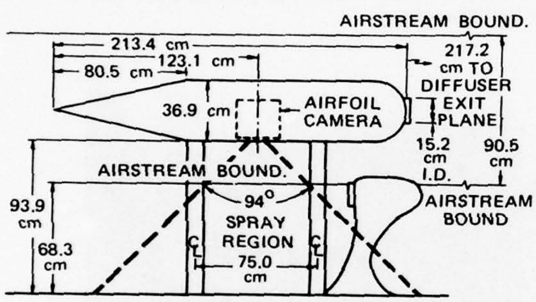

Figure 4. Dimensions of Test Airfoil

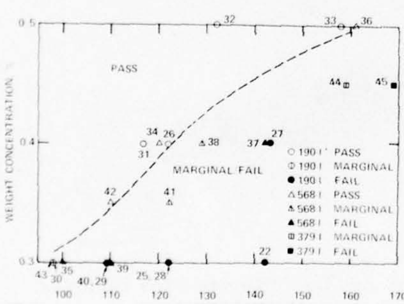

Figure 5. Fire Suppression Effectiveness Envelope for FM-9 in Jet A

ENGINE TESTS

A single Dart engine combustor-can test rig was used by the FAA to provide an initial assessment of the performance of 0.7 percent XD-8132 modified fuel under engine operational conditions. It was found that combustion could not be maintained at fuel manifold pressures below 135 psig. At 135 psig, there was less complete combustion with a correspondingly different combustion profile as compared to that observed under identical conditions with conventional fuel. The combustion profile improved as the fuel manifold pressure was increased up to 200 psig where the profile approached that observed with conventional fuel.

The J-71 engines in the RB-66 used for the third modified fuel crash test were started on conventional fuel and switched to 0.5 percent XD-8132 modified fuel at 84 percent RPM (200 psig fuel manifold pressure). The engine RPM and exhaust gas temperature did not change when the switchover was made. The engines were then throttled back on the modified fuel to 72 percent RPM and operated satisfactorily at this condition during the crash test.

The Army supported a 50-hour preflight rating test on T-63 helicopter engine using 0.2 percent AM-1 modified fuel and also found it necessary to start on conventional fuel and switch to modified fuel. Engine performance at flight idle and above was not adversely affected by the modified fuel, but operation at ground idle was marginal. Final inspection of the disassembled engine parts did not reveal any detrimental effects of the additive (Ref. 13).

A possible solution to the engine start problem is to degrade the size of the antimist additive molecules to make the fuel acceptable to the engine fuel control and fuel nozzles. Tests on a Spey engine at the National Gas Turbine Establishment in England with predegraded FM-9 modified fuel indicated no differences in performance from that obtained with conventional fuel and that the engine could be started and restarted with no difficulty. It is concluded from these tests that no serious engine problems will occur if the modified fuel is substantially degraded prior to the fuel control and methods of producing such degradation are being investigated in the United States and United Kingdom (Ref. 16).

AIRCRAFT FUEL SYSTEM TESTS

The Lockheed-Georgia Company investigated the compatibility of 0.3 percent AM-1 and FM-4 with fuel system components in the C-5A fuel systems simulator under takeoff, climb, cruise, and descent conditions. It was found that the system did not operate satisfactorily with the AM-1 modified fuel since the ejector pump system

did not function and the engine gear pump cavitated at 29,000 feet during the simulated climb. This difficulty was not experienced with less viscous FM-4 fuel during climb and cruise at 40,000 feet; however, the engine pump filter was bypassed because of the high pressure drop across the filter (Ref. 17). Progressive deterioration of the antimist characteristics of the fuel in the boost pump sump box was noted during the 3-hour test. However, the sump box volume is extremely small compared to the tank capacity and the fuel contained therein would probably have a minimal effect on the antimist characteristics of the fuel released during a crash.

The Army investigated the compatibility of 0.2 percent AM-1 with UH-ID/H helicopter fuel system components and also found that this modified fuel did not permit ejector pump operation. In the case of the electric boost pump, the discharge rate was about 60 percent of the flow rate developed with conventional fuel (Ref. 13).

Pumping efficiency tests conducted by the Royal Aircraft Establishment have indicated that the pump efficiency with 0.3 percent FM-9 is about 90 percent of that with conventional fuel. The RAE is currently sponsoring system compatibility tests with 0.3 percent FM-9 in the BAC-1-11 fuel system simulator (Ref. 6). The Navy may also conduct a A-7 airplane system component and TF-30 compatibility tests with FM-9.

FUTURE TECHNICAL, EXPERIMENTAL PROJECTS

A joint program with the United Kingdom, NASA, and elements of the DOD will undertake specific projects to determine the feasibility of using antimisting kerosene (AMK) as a fuel that will preclude the fire-ball when fuel tanks are ruptured in an otherwise impact-survivable crash.

1. Large-scale crash tests will be conducted at the Navy Lakehurst Test Facilities using Surplus SP-2H aircraft to evaluate antimisting kerosene as a fire-resistant fuel that would preclude the fireball associated with many aircraft accidents. The aircraft is used only as a low cost method of testing large fuel tanks under realistic conditions. This is not a full-scale aircraft system test.

2. A project using an airframe manufacturer's wing tank fuel system (C-141) simulator will be initiated to determine any major system compatibility problems when using antimisting kerosene as a fuel.

3. The National Aviation Facilities Experimental Center (NAFEC) will undertake to design and fabricate a fuel air shear test facility that can produce realistic fuel release rate and controllable air speeds. This facility can be used to evaluate candidate antimisting fuels in an economical and repeatable manner.

4. NAFEC will write a preliminary specification for antimising kerosene.

5. NAFEC will undertake to evaluate fuel system components when exposed to antimisting kerosene.

6. Under contract and in cooperation with NASA-Lewis, projects will be undertaken to determine the level to which an antimisting fuel must be degraded (or restored to some degree of the base fuel) to minimize engine operating problems. Concepts to restore the fuel to the necessary level will be identified and prototype device built for experimental use. A means of measuring the state or safety level of antimisting fuel will be developed.

7. The United Kingdom will develop a means of producing antimisting kerosene at acceptable cost and in quantities required by the complete program. They will demonstrate a means of blending the additive at realistic aircraft refueling rates. They will investigate the feasibility of degrading AMK to an acceptable level by means of a rotary mechanical device.

8. A prototype means of degrading (restoring) AMK to some degree of neat kerosene will be developed to allow engine operation with least changes possible.

SUMMARY

In the event of ignition of fuel spillage from severed wings or damaged fuel tanks, the use of antimisting fuel is considered to be the only currently feasible concept for reducing the post-crash fire hazard.

Accident experience indicates that the thermal fatalities resulting from impact-survivable accidents where such spillage occurred represent about 32 percent of the fatalities in the total number of survivable accidents. Engine and aircraft fuel system compatibility problems exist and efforts are underway in the United States and United Kingdom to identify and resolve the problems. The intentional degradation of modified fuel for unrestricted engine operation is the major compatibility factor which must be

handled. A method for refueling aircraft without degrading the antimist characteristics must also be developed. Dependent upon demonstrating the safety benefits under realistic crash conditions in 1978-79, the FAA program anticipates that any system design changes can be developed by 1982 and operational and flight tests can be conducted in 1983 to assist in the ultimate use of modified fuel by turbine helicopters and eventually, by turbine aircraft. These tests will verify a modified fuel specification that can be used to qualify engines and aircraft so that the post-crash fire hazard can be reduced significantly through the use of modified fuel without reducing the operational reliability and performance of conventional fuel.

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CABIN FIRE SAFETY R&D PROGRAM

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BIOGRAPHIES

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ABSTRACT

This paper describes and discusses the Federal Aviation Administration's Cabin Fire Safety R&D Program. The program is being conducted under a coordinated effort by the FAA's National Aviation Facilities Experimental Center (NAFEC), Civil Aeromedical Institute (CAMI) and Systems Research and Development Service (SRDS) Aircraft R&D Program Office. Regulations prior to 1972 were principally concerned with the problem of material's flammability. The FAA's current effort, however, is addressing the problem as a system because accident experience since 1972 has shown that the hazards of a cabin fire environment are complementary and should be considered simultaneously.

The systems approach involves three major elements: The first is the definition of the critical cabin fire mode by use of simulated full-scale and small-scale fires. The second is the improvement of the fire safety characteristics of cabin materials. The third is a fire-management approach which adapts the safety of conventional fire control techniques.

The paper discusses the results and status of NAFEC's R&D work on simulated cabin fire testing and development of improved laboratory test apparatus and techniques; its investigations in fire-management are also described. CAMI's work in the area of animal testing and toxic gas measurements is tabulated. SRDS program office development of cabin fire computer programs and a combined hazard index method for ranking materials is discussed. The FAA program is coordinated with similar work underway at NASA and the National Bureau of Standards.

BACKGROUND

An analysis of past-impact survivable turbine-powered transport aircraft accidents (Ref. 3) reveals that nearly 95 percent of the fatalities occur in accidents where post-crash fire occurred. Fire and its associated hazards, such as heat, smoke and toxic gases, are estimated to be the cause of 40 percent of the fatalities in such accidents.

Commercial transport aircraft cabins, as well as most general aviation cabins, are aesthetically furnished and trimmed with many different polymeric materials. Such materials, however, can represent a significant fire load; i.e., 9400 lbs. in a typical wide-body transport, and when exposed to a persistent ignition source, and self-sustaining fire, can create intense heat, dense smoke, toxic gases and combustible products causing flash fires.

The FAA has, for several years, sought solutions to the cabin fire safety problem. Existing Federal Air Regulation FAR 25.853, (Ref. 1), dealing with the self-extinguishing requirements of interior materials under modest ignition sources, reflects the results of R&D work on flammability in 1966 and prior years. Recent Notices of Proposed Rulemaking relating to smoke and toxic gas emissions of cabin materials (Ref. NPRM 75-3 and ANPRM 74-38 (Ref. 4, 6)),

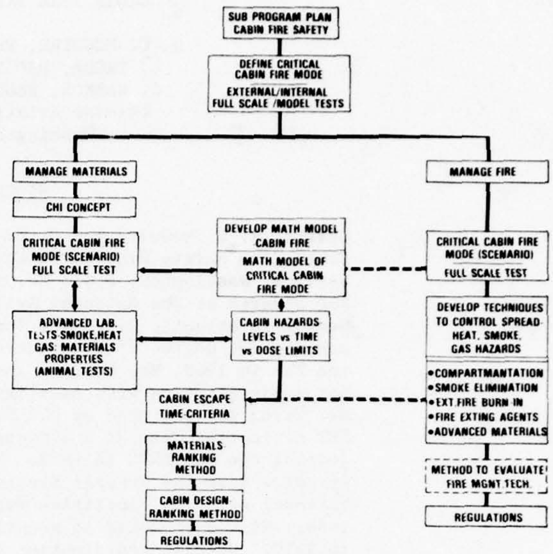


Figure 1. Program Plan - Cabin Fire Safety

were attempts to introduce regulations based on criteria generalized from experiments by FAA, industry and National Bureau of Standards during the 1967-73 period. Responses to these notices, in association with recent accident experience and advancing state-of-the-art, showed the scope of the cabin fire problem to be substantially greater than previously supposed. The R&D program was therefore modified to address cabin fire safety as a systems problem.

The responses also prompted recognition of the need for the planning and construction of a full-scale wide body cabin fire test facility. This was achieved by the acquisition, modification and instrumentation of a C-133 aircraft into a simulated wide body transport, which is presently operational at NAFEC. A well equipped and well staffed chemistry laboratory was also constructed at NAFEC to provide the resources needed for toxic gas analysis. The toxicology laboratory of the Civil Aeromedical Institute provides expertise in animal test and physiological response.

FAA's appreciation of the greater scope and complexity of the cabin fire problem and the requirement for systems solutions, suggested the concept of ranking individual cabin interior materials for their collective combustion hazards; i.e., heat, smoke, toxic gases, as they influence a cabin occupant. This development is now in process by a contractor. A corresponding task is being performed under contract by a university research organization addressing the combustion hazards created by a cabin fire involving several materials.

The potential benefits of using fire control techniques were studied by FAA as early as 1965. Similar but more comprehesnive studies of the ability of cabin divider systems to control the spread of fire hazards between sections of a narrow body aircraft cabin were conducted by the Aerospace Industries Association about 1966. The FAA conducted broader tests in 1974 and 1975 to evaluate the efficiency of a Halon 1301 cabin fire extinguisher system in controlling simulated seat fires in the cabin, and also impeding the penetration of external post-crash fuel fire into the cabin. The results suggested that these studies be continued in wide-body type cabin. Such studies are planned.

The FAA's current R&D cabin safety effort is therefore very broad and comprehensive and involves SRDS, NAFEC, CAMI, NASA, NBS and industry.

TECHNICAL APPROACH

A systems approach to solutions to the cabin fire problems was initiated about 1973. The program plan is shown in Figure 1. It involves three primary tasks. One task is directed toward improving the fire safety characteristics of cabin interior materials; another is directed toward the adaptation of conventional fire control techniques such as fire detection and extinguishing systems, fire hardened compartments and novel smoke removal systems. The third, as shown on the planning chart, is necessary to define the critical cabin fire mode; i.e., the post-crash cabin fire scenario, which causes fatalities during an otherwise successful emergency evacuation. In the past, most investigators have relied on accident records for such cues. For example, lavatory fires have been simulated by burning cabin trash in mock-up lavatories; cabin fires have been simulated in mock-up cabin sections by ignition of seats and sidewall/ceiling systems systems; fuel spill external fires have been simulated by small pan fires near door openings. However, the primary source of the cabin hazards and their rate of build-up from (1) external fuel spill fire or (2) burning interior cabin materials, or both, have never been defined. For this reason, the FAA constructed at NAFEC a full-scale cabin fire test facility simulating wide-body transport cabin in length, width and volume. Tests directed toward characterizing the primary cabin hazard source and its magnitude and distribution in the cabin, have been underway at NAFEC for several months. The results of this work are elsewhere reported in this paper.

Also located at NAFEC are (1) a completely equipped chemistry laboratory; (2) a physical properties burn test laboratory; and (3) a physical scale modeling facility. These support the full-scale cabin fire tests and also expedite needed solutions and data for other elements of the cabin fire problem.

Manage Materials Task

The Manage Materials task envisions a concept for ranking a cabin material for its combustion hazards as they affect a cabin occupant attempting an emergency escape from a post-crash cabin fire. This approach is called the Combined Hazard Index (CHI). A contract for the development of this methodology was awarded to the Douglas Aircraft Company, Long Beach, California, in September 1977. It is a multi-year effort consisting of three phases to facilitate cost-effective control of the task. The first phase is a detailed description of the approach being used to develop the CHI method. Phase 2 is the development phase; Phase 3 is the validation of the method. The development task will utilize typical wide area cabin materials such as wall panel structures, seat cushions, and wool rugs. Phase 2 requires a material's combustion hazards to be measured by an integrated set of laboratory equipment (Figure 2) so that the hazards data when input in a cabin fire math model will provide calculated time-history levels of heat, smoke and gas hazards at any location in the cabin. The hazard levels and preselected human dose limits will identify the time-integrated hazard doses to which the victim can be subjected during the emergency evacuation process. Thus, the time to incapacitation and time remaining-to-escape can be calculated and the potential fire safety of the material can be rated. For example, a burning material producing combustion hazards levels resulting in an incapacitating "dose" in less than 90 seconds escape time would be an unacceptable material.

Since the critical cabin fire mode, as being developed by NAFEC, isnot yet available, the CHI development is based on an accident scenario that occurred at London Airport (Ref. 18) in which an engine was torn off during the landing and a fuel spill fire ensued. The spreading fire and radiant/convective heat entered the cabin via an open galley door thus exposing the interior materials to the flames and heat thus igniting the materials which produced heat, smoke, and gas emissions in the cabin. The thermal environment used to test and burn the materials under full-scale conditions to develop the CHI will be based on this scenario.

Figure 3 shows a schematic of the proposed full-scale test set-up for each material. The test location would be at one end of the test cabin with ventilation air entering at that end to simulate conditions of the accident when the aft galley door was open and bathed in flames. The same air flow will be used in both the computer program and the full-scale cabin fire tests.

CHI Laboratory Test Equipment

An evaluation of laboratory test methods resulted in selection of a combined set of state-of-the-art instruments to measure all of the parameters. This combined instrumentation is referred to as CHAS (Combined Hazards Analysis System) and is collectively illustrated in Figure 2. The CHAS integrated laboratory test system is essentially a modified Ohio State heat release rate calorimeter. The modifications include:

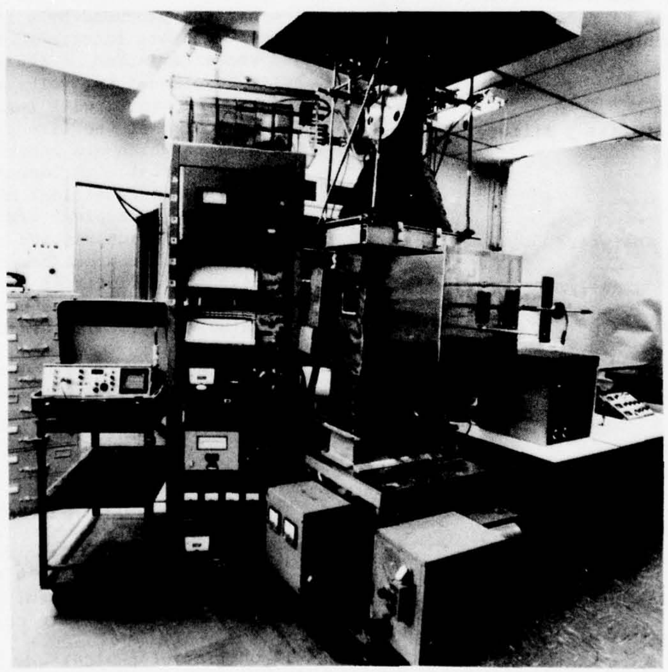


Figure 2. Materials Combustion Hazards Analysis System (CHAS)

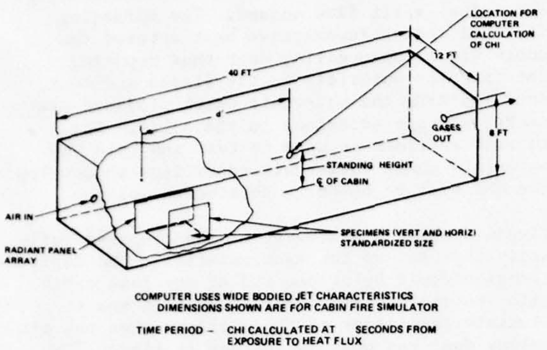


Figure 3. Materials Full-Scale Test - CHI

1. Sampling System

   a. Gas sampling probe near base of stack on HRR chamber.

   b. Gas sampling loop for time interval sampling of target gases by specialized chemical methods (spectrometric, spectroscopic, specific ion electrode, polarographic, gas chromatographic (GC), or GC/mass spectrometric methods).

   c. Two pumped gas sampling loops with gas control valves and flowmeters for monitoring specific combustion gases in real time during a burn test, and for introducing known fractions into the animal exposure chamber.

   d. Smoke particulate assay filters and acid gas scrubbers.

2. Instrumentation

   a. CO_2, CO and O_2 analyzers

   b. Total hydrocarbon analyzer

   c. HCN analyzer

   d. Gas chromatograph - Mass Spectrometer Equipment

   e. Vacuum pumps

   f. Control valves (flow control console)

   g. Strip chart recorders

   h. Data Acquisition System, Calculator, and Plotter

   i. Thermocouples

   j. Sample mass loss measurement system

The animal test equipment incorporated with CHAS will consist of a multiple rat test system instrumented to obtain time to incapacitation in a visual or smoke-obscured environment.

Cabin Fire Computer Program

A nine zone cabin Fortran Computer fire analysis program and thermodynamic relations concept will be used for the CHI method (Figure 4). Applicable portions of cabin fire models being evaluated by the National Bureau of Standards' Mathematical Fire Modeling Committee will be considered.

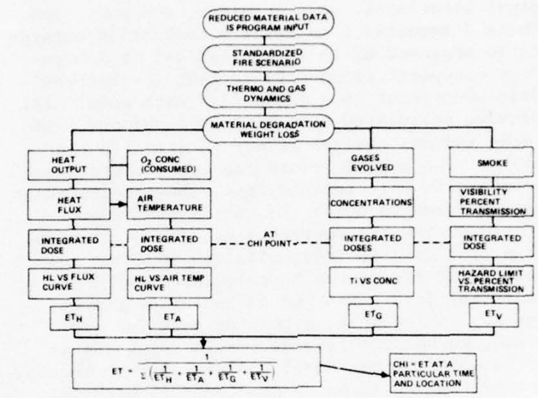


Figure 4. CHI Computer Program Flow Diagram

The hazards produced by a fire in an aircraft compartment are functions of many variables. The characteristics of the compartment with respect to dimensions, volumes, ventilation rate and flow dynamics, wall insulation characteristics and size of the fire affect the magnitude of the hazards which are generated. To evaluate a burning material with respect to its combustion hazards, these conditions must be written into the program. A typical wide-body jet cabin will define the characteristics of the compartment used in the fire model computer program. The fire scenario identifies the characteristics of the initiating fire; the candidate materials will be evaluated for this selected fire scenario.

The CHI rating then is computed for a wide-body cabin and a selected fire scenario. It is also a function of material location, orientation, and quantity.

If it is desired to evaluate the material for some other size aircraft compartment, orientation or quantity of usage, the fire model computer program could be run for a particular case by describing the alternate usage characteristics, etc., in the program. Thus any particular aircraft compartment fire can be studied.

This outline of the CHI project is only a limited description of the entire program. The Phase 2 effort has only recently started. Hence

there is little to report in terms of accomplishments at this time.

DACFIR Cabin Fire Simulation

It will be noted that the CHI method is being designed to evaluate one cabin material. How, then, will the entire cabin material systems be accounted for in terms of cabin fire safety? This question is being addressed under another project contracted to the University of Dayton Research Institute. UDRI has been developing a mathematical model of a cabin fire which is programmed to predict the propagation rate of the fire between adjacent cabin materials, for a given ignition source. It is also being further developed to describe the spatial distribution rate of heat, smoke and gas hazards generated by the burning materials. The computer program as developed is reported in Ref. 12 and depicted by Figure 5. A current contract involving the Boeing Company, NASA-LBJ Center, will validate the predictive capability of this model by comparing its outputs with data obtained by full-scale burn tests of as many as seven different typical cabin materials. The model, when developed, could be used as a cabin-fire safety design tool. As indicated on the program plan (Figure 1) the end product of the entire Manage Materials safety is support of the regulatory process.

crew after an impact-survivable accident. Some task elements in theplan, such as compartmentation and fire suppressant systems, have already been cursorily explored.

Approach concepts which represent the final Fire Management product can be defined only in general terms at this time. The program has both long-term and short-term goals which will lead to providing of criteria and/or regulations as appropriate for the various concepts that will have been addressed and evaluated. Each concept must be investigated in order to establish its ability to provide for additional safe passenger escape time. Each concept must also show adequate reliability with minimum maintenance during the life cycle of the airplane. The resulting systems must be such that the selection of one or more concepts must not interact in a manner that could provide a greater hazard to safety than if each had been individually implemented.

Several different concepts will be pursued to determine the suitability for new production and service aircraft. These concepts must be cost-effective and sufficiently reliable to provide a measurable degree of improvement during emergency cabin fire conditions. Part of the plan will be to use a method by which an appropriate fire analysis assessment of protection and

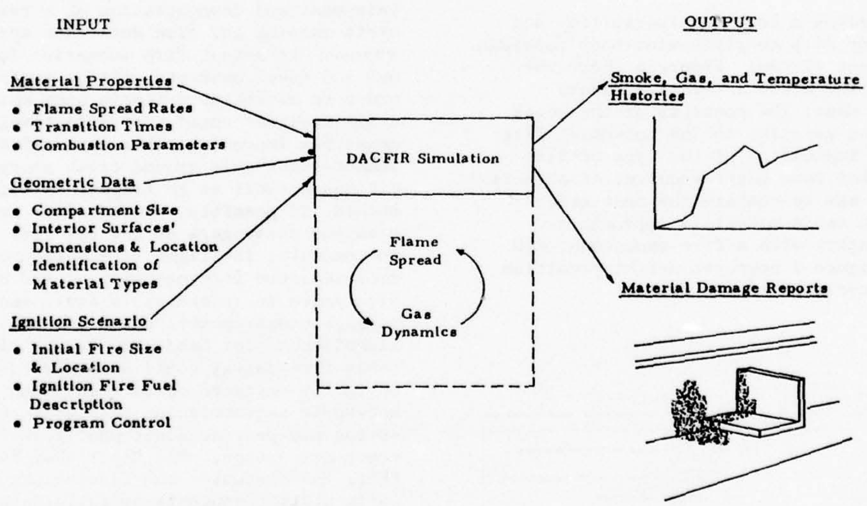


Figure 5. DACFIR Cabin Fire Simulation Computer Program

Fire Management Task

The Fire Management task is designed to complement and supplement the materials management approach and othercabin fire safety R&D efforts. Its objectives are to conceive, develop, evaluate and define new concepts of cabin fire hazards control that might be reliably introduced via the regulatory process as part of the aircraft design, and so significantly improve the emergency escape time for passengers and

hazards associated with the varied zones (cabin, cargo, lavatory, equipment, etc.) of the airplane can be made. Some of this effort has already been reported in Ref. 11, 13, 15, 16, and 17. This will permit an assessment of the type of concept that might most appropriately and cost-effectively be applied to provide the fire protection needed for any anticipated inflight or onground fire scenarios.

An explanation of these concepts and elements is contained in detail later in the paper and listed as follows:

1. Detection, Monitoring and Communication Systems

2. Hazard Reduction Concepts (includes compartmentation, suppression, smoke removal,)

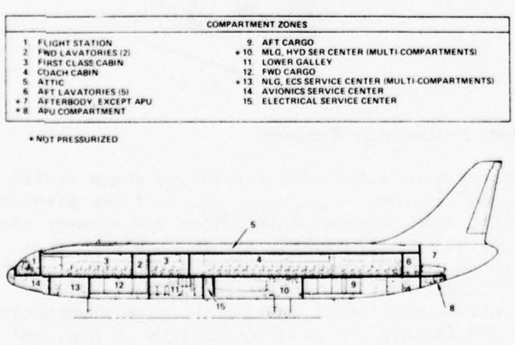
3. Fuselage Fire Hardening Systems (advanced fire hardened materials, detail design).

4. Crew and Passenger Protection

<u>Detection, Monitoring and Communication</u>

The need exists for the evaluation of concepts leading to the development of an early warning aircraft fire detection and monitoring system. Suitable and reliable systems already exist for the propulsion system and cargo compartments. Thus early fire warning system could be expanded to cover other zones of the aircraft fuselage, such as the cabin, lavatories, galleys, overhead wiring compartments, etc. The fire scenarios that must be addressed cover in-flight and ground fire situations both inside and outside of the aircraft. Along with the detectors, a compatible fire warning monitoring system could provide for an early assessment of the fire danger. In conjunction with correct and proper procedures and crew training, the system can provide additional safe escape time.

Ref. 11 describes a Lockheed feasibility and tradeoff study of a complete wide-body fuselage *fire management system.* Figure 6 shows the compartments for which a relative hazard analysis was made. The contents of the zones were evaluated relative to the potential fire loads and an indication of the type of fire protection that zone might require. An objective of the study was to compare the cost effectiveness of a cabin materials approach to cabin fire safety with a fire management R&D approach. Figure 7 compares weight penalties and 20-year cycle operating costs.



Ref. Report No. FAA-RD-76-54

Figure 6. Fuselage Zones Analyzed

ITEM			FIRE MANAGEMENT SYSTEM	IMPROVED MATERIALS
Performance			Provides increased fire safety to all protected zones. Technical problems in area of extinguishing agent toxicity.	Provides some increased fire safety for treated zones. Not effective against carry-on items. Minimal contribution in equipment bays. Technical problems in area of toxicity testing.
Weight Increase (Pounds)			905 (1)	781 (2)
Estimated Costs (Dollars)	Mf'g.*	Recurring	$[illegible]0,000 (1)	$296,000 (2)
	Operating Costs (20 years)	Maintenance & Delay	110,000	50,000(Est.)
		Fuel Costs	274,000	237,000
		Total	384,000 (20 years)	287,000
Time Span to Develop & Incorporate in Production Aircraft (years)			3	4

* Not including non-recurring costs.

Ref. Report No. FAA-RD-76-54

Figure 7. Comparative Data - Fire Management vs Materials Improvement

Results of the analysis show that (1) both material changes and fire management systems involve weight increases; (2) technology exists to provide early warning and fire detection systems; (3) on-board fire suppression systems are technically feasible; and (4) toxicity levels of pyrolized extinguishing agents to which occupants might be exposed should be demonstrated to be acceptable.

Future R&D efforts will concentrate on the development and demonstration of a reliable aircraft warning and fire detection system when exposed to actual fire scenario; for example, *new and novel concepts will be explored in* order to establish criteria upon which an aircraft designer could cost-effectively select a means for improving cabin fire safety during impact-survivable ground crash emergency conditions as well as in flight. All concepts should, if possible, provide fire protection for crew and passengers during all fire situations. For example, in-flight fire safety could benefit from improved fire containment and hardening of fire zones in inaccessible areas such as baggage compartments, etc., and non-toxic extinguishants for habitable areas. Improved cabin fire safety could be achieved by an optimally designed compartmentation system and non-toxic extinguishant that would control fire spread and provide additional time for safe emergency escape. FAA Report No. RD-76-131 (Ref. 15) discusses the feasibility of the compartmentation concepts by full-scale tests performed at NAFEC. Thirty-seven various partition configurations with varying fire loads and *ventilation rates* were investigated. Results are shown in Figures 8 and 9. Future efforts must be directed to the definition of the optimum compartmentation size and evaluation of suitable partition materials to enhance safe and unhindered evacuations.

One of the results of the Lockheed study (Ref. 11) indicated that an onboard suppression system is feasible if toxicity levels of pyrolyzed extinguishing agents can be demon-

strated as minimal. To this end, NAFEC performed full-scale standard body aircraft cabin fire tests of a Halon 1301 suppression system as reported in Ref. 16 and 17.

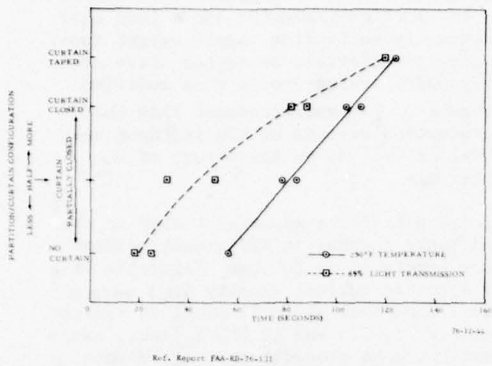


Figure 8. Cabin Curtain Affect on Heat/Smoke Transfer (No Airflow)

The system was evaluated for post-crash internal and external fuel fires. The results generally indicated that intolerable toxic levels of hydrogen fluoride (HF) and hydrogen bromide (HBr) were produced very rapidly inside the cabin during fire suppression, particularly when ventilation such as open doors was present as would be the case during a post-crash emergency evacuation. Therefore, future R&D efforts will evaluate improved extinguishing agents or methods of extinguishment that produce less toxic products in habitable areas of the aircraft cabin.

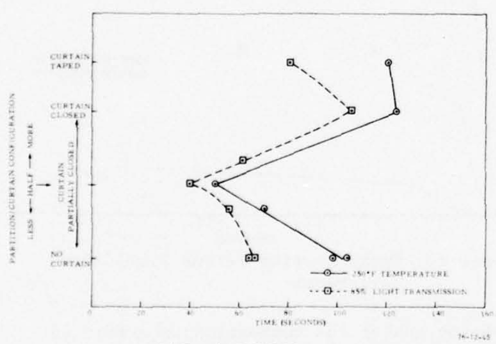


Figure 9. Cabin Curtain Affect on Heat/Smoke Transfer (2800 CFM Airflow)

In an attempt to utilize concepts for fire safety from the industrial and commercial building research, a preliminary test for smoke removal using a model aircraft cabin was evaluated by NAFEC and shown to have sufficient promise to encourage this and other smoke removal concepts as part of the fire management program.

Fire Hardening Concepts

The concept of maintaining fuselage integrity (resistance to fire penetration) during a post-crash fire will be evaluated. This could involve fire hardened fuselage frames and exterior and interior cabin structures. If these concepts prove feasible, they will prevent rapid degradation of the cabin enclosure thus enabling longer escape time.

One objective of the cooperative FAA/NASA cabin fire safety effort is the development of advanced fire safe materials for cost-effective use in the aircraft fuselage. NASA programs have been underway to develop and evaluate fire hardened advanced materials for use in cabin floors, lavatories, seats and sidewalls.

Crew and Passenger Protection

Advanced emergency evacuation procedures and studies of crew and passenger behavior under post-crash fire conditions are being addressed by R&D programs of the FAA Civil Aeromedical Institute (CAMI) in Oklahoma City.

FAA Interservice Cooperation

The description of FAA's concern with cabin fire safety up to this point has dealt mainly with the gross R&D activities under cabin fire program plan. The following paragraphs discuss the degree to which various FAA services and laboratories are cooperating and contributing in developing solutions to the subject problem.

The FAA's in-house fire safety R&D work is performed by three organizations; (1) the National Aviation Facilities Experimental Center (NAFEC) in Atlantic City, New Jersey; (2) the Civil Aeromedical Institute (CAMI) in Oklahoma City; and (3) the Systems Research and Development Service (SRDS), which is the Washington program office.

NAFEC Cabin Fire Safety R&D

The NAFEC Cabin Fire Safety Program (Figure 10) involves four major tasks: (1) the development of new, or the improvement of small-scale

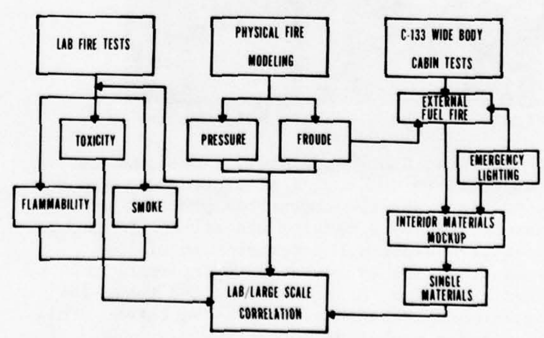


Figure 10. NAFEC Cabin Fire Safety Program

material fire tests for flammability, smoke and toxic gas emissions; (2) the initiation and conducting of physical fire modeling studies; (3) the measurement of full-scale cabin fire hazards in a C-133 test facility under simulated post-crash fire conditions; and (4) the correlation of materials test data from small-scale and large-scale material fire tests. The first three efforts are currently active, while the laboratory/large-scale correlation effort is planned.

Materials Tests/Equipment Development

In the area of fire testing of cabin materials, the greatest activity is in toxicity.

There are relatively modest efforts in flammability and smoke. Regarding flammability tests, in-service cabin materials are being evaluated by five popular test methods; i.e., the vertical Bunsen Burner test; the E-162 Radiant Panel test, thermogravimetric analysis, Limiting Oxygen Index and the Ohio State rate of the heat release apparatus (Figure 11). The objective of this work is to identify an advanced material flammability test.

Figure 11. Heat Release Rate Chamber

In the Ohio State Apparatus, a specimen is subjected to controlled simulated fire exposure conditions and the combustion products are transported by a carrier air stream up through a stack. Usually the temperature of the exhaust stream is measured to determine rate of heat evolution, although smoke and toxic gas emission measurements can also be taken. This test has a number of attractive features; namely, (1) capability of vertical and horizontal specimen orientation; (2) selection of incident heat flux from a range of values; (3) determination of release rate values; and (4) display of rate changes.

Several modifications have been made to the NBS smoke chamber, including installation of a variable radiant heater (capable of 10 Btu/Ft^2-sec), a laser transmissometer and a load cell for continually monitoring sample weight loss. The in-service materials mentioned above are currently under evaluation in this modified smoke chamber. The modifications show that smoke production depends on the incident heat flux level as well as on the nature of the test material.

Preliminary data for a material tested in the modified smoke chamber at different incident heat flux levels is as follows. Figure 12 is a plot of specific optical density (D_s) versus time for a honeycomb sidewall panel at radiant heats of 2.2, 5, 7.5 and 10 Btu/ft^2sec.; large increases in smoke production occur between 2.2 and 5 Btu/ft^2 sec., and 5 and 7.5 Btu/ft^2-sec. The smoke rate profiles are fairly close at 7.5 and 10 Btu/ft^2 sec. The inflection points in the curves correspond to ignition of the specimen. Thus, for a honeycomb panel, smoke production increases monotonically with incident heat flux.

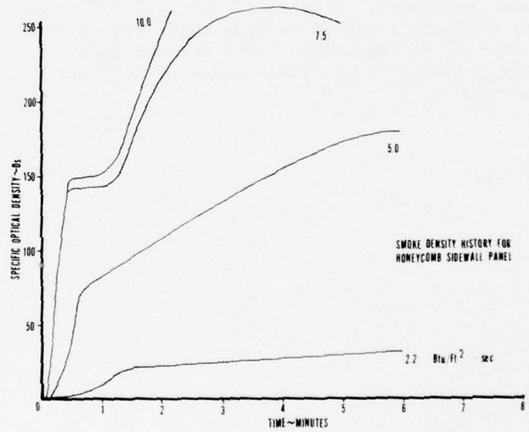


Figure 12. Smoke Density Versus Time-Cabin Wall Panel

A photograph of the combustion tube furnace set-up used for toxic gas emission testing is shown in Figure 13. It is a flow-through type of test and consists essentially of an annular furnace and temperature control module, a quartz combination tube for accommodating the sample material, a vacuum pump for drawing air through the system, a manifold for dividing and passing the combustion effluent into four fritted bubblers containing appropriate collective liquids, and a series of downstream rotameters and a single upstream rotameter for controlling air and effluent flow rates, respectively. The following test conditions

are usually employed; furnace temperature of 600°C, sample weight of 250 milligrams, airflow rate of 2 liters/min. and test duration of 5 minutes.

Physical Scale-Fire Modeling

Another major effort in the NAFEC program in-involves pressure and physical fire modeling

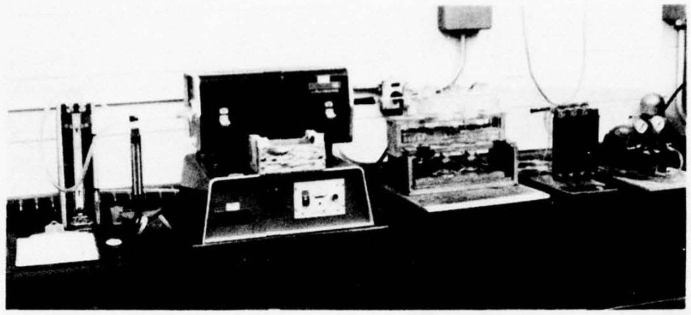


Figure 13. Combustion Tube Furnace

Figure 14 illustrates gas emissions for a series of aircraft cabin materials tested in the tube furnace apparatus by NAFEC in cooperation with the Civil Aeromedical Institute. The materials are arranged within each usage category in the order of decreasing toxicity. For example, highest CO yield was obtained from Material No. 130, a cotton-rayon blend, while the modacrylic drape (No. 127) produced the highest yield of HCN of any of the materials tested, (Ref. 8). Toxicity ranking was accomplished by CAMI using animal response tests reported in Ref. 9.

Work was begun in 1977. A contract was awarded to the Factory Mutual Research Corporation to evaluate the feasibility of burn testing vertical specimens under pressure and the final report is in process. Physical (scaled) modeling fire tests are also in process to study thermal radiation, flame penetration, and smoke and heat accumulation inside a scale-sized cabin caused by an external fuel fire adjacent to a fuselage door.

The tests are being performed inside a building in order to control the test repeatability.

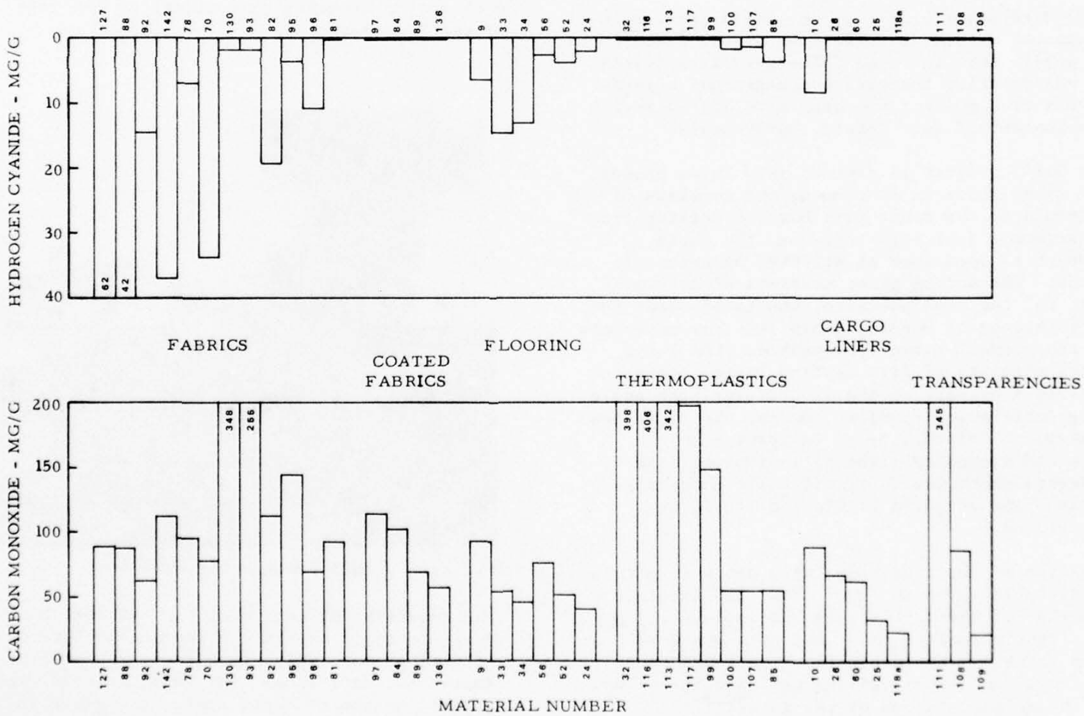


Figure 14. Toxic Gas Emissions - Cabin Materials

Figure 15 shows a fire test of a 4-foot diameter "fuselage." The fire is observed to attach to the tube and neck down to a size smaller than that of the fuel pan. Under quiescent wind conditions, the radiant heat flux inside the tube at the centerline was approximately 1.7 Btu/ft.^{2}-sec.

Figure 15. Scale Fire Test - 4 Ft. Diameter Fuselage

The heat flux on the surface of the tube adjacent to the fire was about 12 Btu/ft.^{2}-sec. Very little flame penetration was observed under no-wind conditions. These are exploratory experiments in search of trends to expedite the C-133 full-scale fire project.

Full-Scale Cabin Fire Tests

The third major effort is the C-133 full-scale, simulated wide-body cabin fire tests. There is an urgent need for such full-scale fire testing to characterize the hazard sources and hazard levels of a post-crash cabin fire and so enable development of fire safety improvements.

The C-133 project is divided into three phases. The first phase is in process and consists of determining the cabin fire hazards arising from an external fuel fire entering the cabin through an open door as affected by external winds. The second phase consists of determining, for the same scenario, the involvement and contribution of burning cabin interior materials to the overall cabin fire hazard. The third phase consists of fire testing large samples of materials as part of the laboratory/large-scale fire correlation studies. During the first two phases, the visibility of in-service and advanced emergency lighting systems will be assessed under the realistic cabin smoke conditions and advanced lighting criteria so identified.

A sketch of the wide-body C-133 cabin fire test facility is shown in Figure 16. The fuselage diameter of the facility is 200 inches, which is slightly smaller than that of a DC-10 (216 inches). The cabin floor extends about 76 feet. An 8-foot ceiling was also installed. The calculated volume of the interior is 13,200 ft.^{3}, making the facility the largest test bed available for the study of wide-body cabin fires. Two standard type "A" door openings about 60 feet apart are installed in one side of the fuselage. The external fuel test fire is adjacent to the forward door while the aft-door exhausts the smoke and gases.

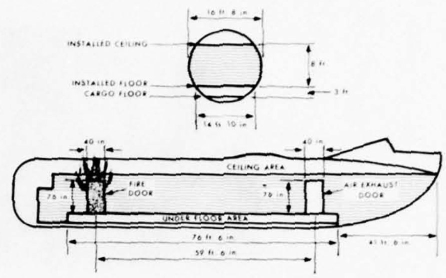


Figure 16. Schematic of C-133 Cabin Fire Test Facility

The full-scale tests simulate a low-impact, survivable post-crash condition accompanied by an external fuel spill fire adjacent to an open door of an intact fuselage. Figure 17 is a photograph of a typical test. To control wind and flame penetration into the cabin, a barrier was initially erected; a fan simulated the wind. As shown in the photograph, a fuel fire of moderate size (4-foot square) produced high flames and thick smoke. Fire corresponding to greater fuel spills have also been tested and show that ambient wind and cabin ventilating areas are as critical as the size of the fuel fire.

Figure 17. Full-Scale Cabin Fire Test - C-133

The immediate objective of the external fuel spill tests is to achieve repeatable hazard conditions for replicate fires. The preliminary test data shows that there is significant stratification of heat, smoke, and gases in the cabin. A temperature-time plot at three symmetry plane elevations, located 35 feet aft

of the fire door is shown in Figure 18. At 5 feet 6 inches, near the head of a standing person, the temperature was considerably higher than at the lower levels - 3 feet 6 inches and at 1 foot, equivalent to the head of a crawling person. For example, a temperature of 300°F was reached in 30 seconds at 5 feet 6 inches, versus 2-1/2 minutes for the same temperature at 3 feet 6 inches. The cooler region near the floor is extensive, as evidenced by the two lower-level curves which are practically coincident over the first several minutes. This qualitative condition appears to prevail through the cabin.

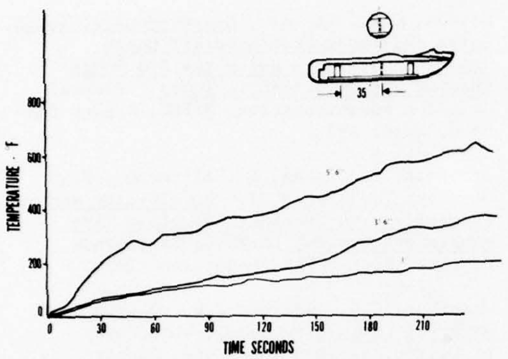


Figure 18. Stratification of Cabin Temperature vs Time - Cabin Center

Figure 19 shows the carbon dioxide (CO_2) concentration history at two symmetry plane elevations located 35 feet aft of the fire. The CO_2 concentration is slightly higher at 7 feet 11 inches (1 inch below ceiling) than at 5 feet 6 inches. However, the degree of stratification of CO was far more significant at this station. The maximum CO concentration at the ceiling sampling location was approximately 0.5 percent (or 5000 ppm). But at 5 feet 6 inches, CO was not detectable instrumentally with the gas analyzer (Beckman IR analyzer, Model 864) which had a threshold detection limit of less than 100 ppm. Thus, it appears that the degree of stratification of gases may be strongly related to molecular weight. The amount of oxygen (O_2) depletion at this station was found to be insignificant. As expected, the lowest O_2 concentration was detected near the ceiling, but never was below about 18 percent.

The cabin ceiling temperature at the fire location was about 500-700°F higher than at the exhaust door. The ceiling temperature increased at a rate of about 100°F per minute.

The three preliminary findings with regard to the cabin hazards measured during these tests are:

1. Significant stratification of heat, smoke and toxic gases occurred.

2. Heat and smoke hazards appear more significant than carbon monoxide and carbon dioxide.

3. Oxgen depletion was insignificant for the cabin as ventilated by two open doors.

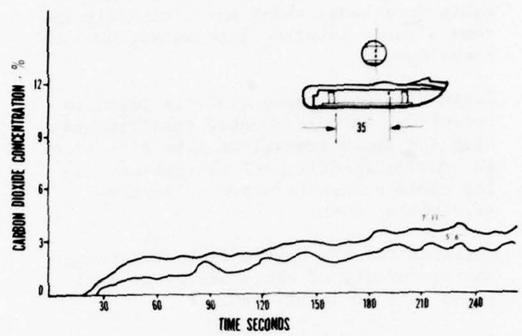


Figure 19. Stratification of Cabin Dioxide vs Time - Cabin Center

SUMMARY

The FAA has been aware of the cabin fire safety problem for some time and has issued regulations over the years to control the flammability of materials used in cabin interiors. These have been very effective in preventing small ignitions in the cabin from spreading into large fires. Accident records show that most fatalities occur under post-crash conditions wherein burning fuel spills or another persistent high energy ignition source ignites the polymeric cabin interior materials. The time-history of the cabin hazards created by the combustion of jet fuel, on one hand, and cabin materials on the other is being investigated by FAA to define the critical cabin fire mode. In support of this R&D, a technique is being developed by which candidate cabin materials can be individually ranked for collective combustion hazards as they influence a cabin occupant. Similarly, math modeling techniques are being developed to predict the fire safety of a cabin interior in its design stage. Safety goals are also being addressed in a complementary approach based on conventional fire management techniques. The cooperative effort toward the safety goal involves the Civil Aeromedical Institute, National Aviation Facilities Experimental Center, and the SRDS program office in Washington, D.C. The work is also coordinated with the fire safety R&D studies being conducted by NASA and NBS. The FAA's R&D work is expected to provide data and criteria as follows:

1. The C-133 test program will determine cabin hazards associated with jet fuel fires and the burning of single and multiple interior cabin materials. The

reduced scale fuselage tests will determine whether valid scaling relationships can be established to predict cabin fire behavior similar to full-scale burn test results.

2. A Combined Hazard Index (CHI) will be developed to rank high usage cabin interior materials for the hazards of their combustion products as they affect a cabin occupant.

3. The NASA-Houston Center will assist in validating and improving the UDRI dynamic cabin fire model which may ultimately become a cabin interior fire safety design technique.

4. Cabin fire management criteria based on detection, extinguishants, compartmentation and smoke removal will be effective in providing additional evacuation time for cabin occupants after an impact-survivable crash.

5. Criteria for the most efficient location, and durability of cabin emergency exit signs will be identified.

This R&D information will provide Flight Standards with the data base, criteria and, in some cases, a means of demonstrating compliance with proposed safety improvements.

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ESTABLISHMENT OF AN AIRCRAFT EXHAUST EMISSIONS TECHNICAL DATA BASE

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BIOGRAPHY

William T. Westfield has been program manager of the Federal Aviation Administration (FAA) Aircraft Emissions Research Program since its initiation in 1968. He came to FAA in 1967 from the United States Naval Air Propulsion Center in Trenton, New Jersey where he spent 12 1/2 years in propulsion oriented work. He also worked for Westinghouse Aviation Gas Turbine Division, Philadelphia and Kansas City after receiving his B.S. in Mechanical Engineering from Drexel Institute of Technology in 1953.

ABSTRACT

Background of the legislative history of the Environmental Protection Agency (EPA) aircraft emission standards issued in 1973 is reviewed. FAA assessment of the technical data base necesary for regulation and actions to develop the needed data base are described and results to date are summarized. Present and future projects aimed at improving measurement and assessment techniques are discussed.

BACKGROUND

Limitation of exhaust emission amounts from aircraft and aircraft engines were set by EPA standards in July 1973, as a result of directives contained in the Clean Air Amendments of 1970, Public Law 91-604.

These limitations, shown in Table 1, are time phased, and reflected an improvement in emissions of the engines in the fleet to an extent the EPA felt was supportable by the technology. The National Aeronautics and Space Administration (NASA) had begun a comprehensive effort to attempt to develop combustion systems that would meet the EPA requirements. However, at the time of EPA initial release, this work has still considered conceptual and many years from operational hardware. Implementation, again by direction of Public Law 91-604, is the function of FAA.

The EPA based its 1973 determination that limitations were necessary on a data collection effort by their contractors between June and September 1971. The analysis of this data was done by Calspan, Inc. for EPA and was reported in November 1971.[2]

EPA, in its 1973 issuance, recognized the severity of some of these requirements for aircraft and therefore stated that periodic reassessment of the technology would be held to assure the equity of the requirements. Such a reassessment was held in January 1977 and as a result, significant changes in the limitations were made, and others proposed. These are also shown in Table I and Figure 1.

The most notable changes are that the limitations on general aviation aircraft has been removed and the limiting value of the nitrogen oxides was relaxed. The latter change tending to support the fact that the technology could not produce what EPA had initially desired. The advanced technology combustors have yet to be converted from research to operational hardware and placed into service evaluation, a process estimated to consume about six years.

The limits on auxiliary power units, low thrust turbine engines and all but large turboprops have also been deleted. Between the initial 1973 limits and the proposed revisions of Table 1, FAA had begun its steps toward implementation.

An analysis of the then existing data identified gap areas which would have to be filled prior to being in a position of establishing a regulation to implement the EPA limits. The purpose of this paper is to describe some of the basic thinking that led to the present FAA Research and Development (R&D) program in emissions, the most significant efforts, the progress and the results to date.

CURRENT

TYPE	EPAP* HC	EPAP* CO	EPAP* NO_x	EFFECTIVITY DATE
G/A PISTON	.0019	.042	.0015	DECEMBER 31, 1979
TURBOPROP (NME)*	4.9	26.8	12.9	JANUARY 1, 1979
APU	0.4	5.0	3.0	JANUARY 1, 1979
TURBOJET/TURBOFAN				
- 0 to 8000 lb.	1.6	9.4	3.7	JANUARY 1, 1979
- 8000 lb. up (NME)*	0.8	4.3	3.0	JANUARY 1, 1979
- 8000 lb. up (NCE)*	0.4	3.0	3.0	JANUARY 1, 1981
- In-Use	-------	N O N E	-------	

PROPOSED

TYPE	HC	CO	NO_x	EFFECTIVITY DATE
G/A PISTON	-------	N O N E	-------	
TURBOPROP (NCE)				
2500 shp*	2.0	5.0	13.0	JANUARY 1, 1984
APU	-------	N O N E	-------	
TURBOJET/TURBOFAN				
- 6000 lb. up (NME)	See Figure 1			JANUARY 1, 1981
- 6000 lb. up (NCE)	See Figure 1			JANUARY 1, 1984
- In-Use 12000 lb and JT8D	Same as NME, Figure 1, Except NO_x = None			

NOTE: NME = Newly Manufactured Engines
NCE = Newly Certified Engines
EPAP = lb. Pollutant/1000 lb. Thrust Hours/Cycle
shp = Shaft Horsepower

TABLE I - CURRENT AND PROPOSED EPA EXHAUST EMISSION LIMITATIONS

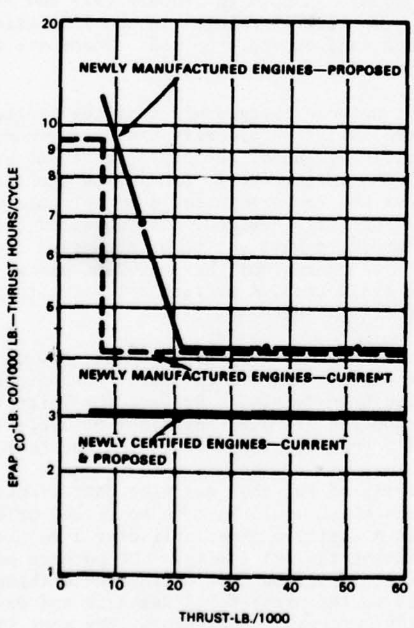


FIGURE 1a. CARBON MONOXIDE LIMITATIONS

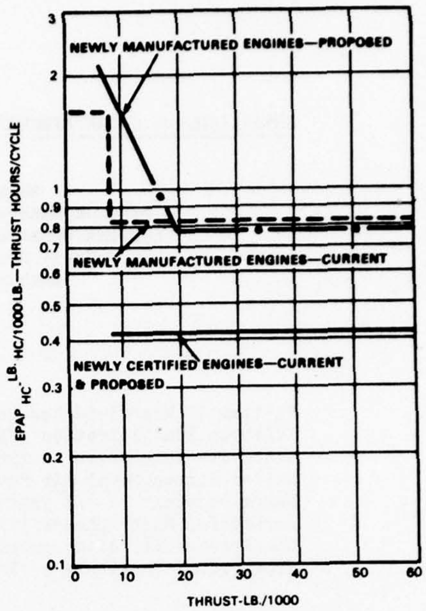
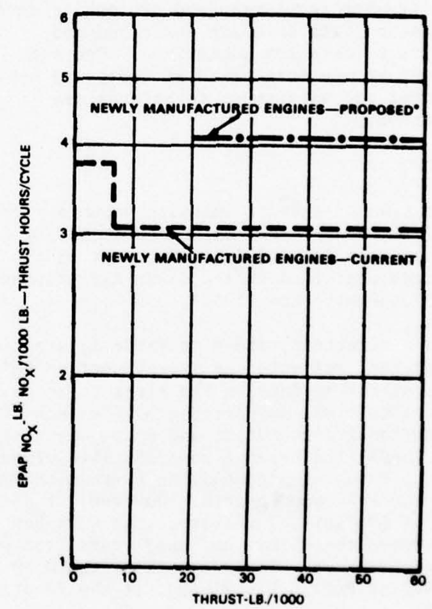


FIGURE 1b. HYDROCARBON LIMITATIONS



*CORRECTED TO RATED PRESSURE RATIO = 26.0

FIGURE 1c. NITROGEN OXIDE LIMITATIONS

PRODUCTS/EXPECTED RESULTS

The major R&D elements needed to permit FAA action were determined to be as follows:

(a) uniformity of measurement and analysis techniques within a framework that covered the range of types of engines and/or aircraft to be regulated,

(b) documentation of the existing capability of the engines within the specified framework to meet the projected requirements,

(c) establishment of the feasibility of the engines within the specified framework to safely meet the projected requirements,

(d) identification of areas where the technology was being over-extended in meeting the projected requirements.

TECHNICAL APPROACH

In reviewing the information contained in EPA reports[1,2] the FAA realized that a very basic problem with the available data base was that the measurement techniques and equipment were not fully developed, reliable or repeatable. A conclusion[2] was made that in considering data on an engine type, variability comes from two sources, measurement or experimental error or from the engine itself. If measurement errors dominated, several replicate tests of a few engines would give the best information but if the engine variability dominated, tests of multiple engines would be best. What was not addressed to FAA satisfaction was that either of the above situations could occur and no solution was presented as to how to resolve the relative dominance.

Eight different teams were used by EPA to make the measurements. No correlation of equipment, procedures, etc. were attempted. It therefore appeared quite possible that eight sets of equipment, used in eight different ways, in eight different locations, by eight different operators were responsible for the data base. To compound the problem further, the sampling probe configuration was not fixed for the different tests.

The conclusion,[2] that the variation in emissions for a set of engines was often as great as the measurement itself, led FAA to its initial step, that is, of fixing the measurement collection probe to a configuration that would be common to all tests.

In the FAA test programs, prior to design of a sampling probe, detailed traverses of engine exhausts were made using a single point probe. The number of points sampled for a particular engine was governed by the exhaust area since all sampling was done on a two-inch square g grid. For the JT8D-type engine, this resulted in 177 individual sampling points. The data was then operated upon statistically to determine, for the least number of locations, where the average emission level would be located. This procedure was repeated for all engine power conditions, for each of the pollutant emissions of interest, carbon monoxide (CO), unburned hydrocarbons (HC) and oxides of nitrogen (NO_x). In addition, carbon dioxide (CO_2) was also measure because of its close relationship to the combustion process. The patterns were reported[3] in 1976 for the JT8D engine.

The results of this analysis was a design for a sampling probe that would give a representative emission level. The basic design is shown in Figure 2 and an aircraft installation of the probe is shown in Figure 3.

Thus far, indications are that satisfactory and repeatable data is obtained with this design.[6,5] Barring any adverse data from the remainder of the work, this design will form the basis of the research recommendation for a certification sampling probe.

The variability problem is being dealt with "in parts," much as was done with the sampling probe. Encompassed in the term "variability" is that due to production tolerances, different ambient conditions at time of test, facility and hardware differences, and quite possibly others which have not yet been identified.

FAA's approach has been to establish the impact of the ambient test conditions upon emission levels. Initially an empirical approach[6] was utilized as was reported in 1976. This was followed by tests where engines were operated over their full range of power on days when temperature, barometric pressure, and specific humidity differed. The trends that developed were consistent enough to allow mathematical representation of the trend. It was apparent the form of the equation was the same for each pollutant provided the basic engine type was the same. Within each engine type, the constants in the equations varied with particular engine type.

FAA also initiated a program to determine the rate at which engine emissions change with operating time. The impetus for this effort was the EPA requirement that each engine would not emit more pollutant throughout its lifetime than the engine would be allowed to emit when new.

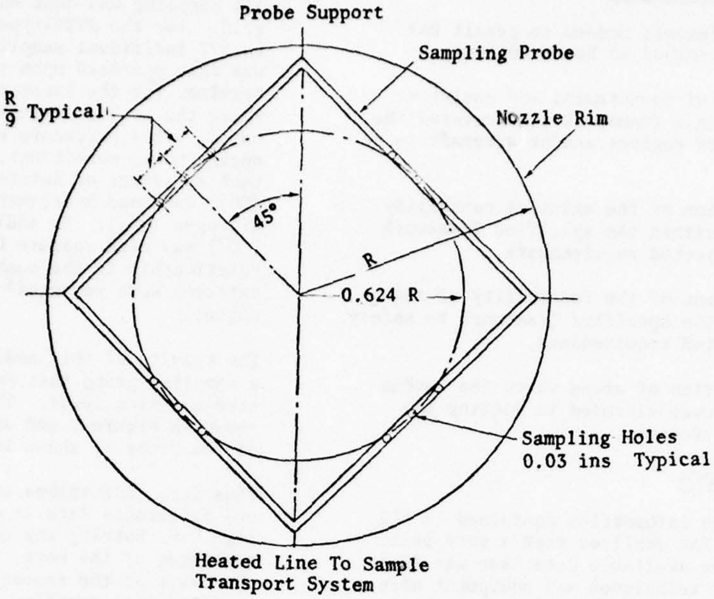
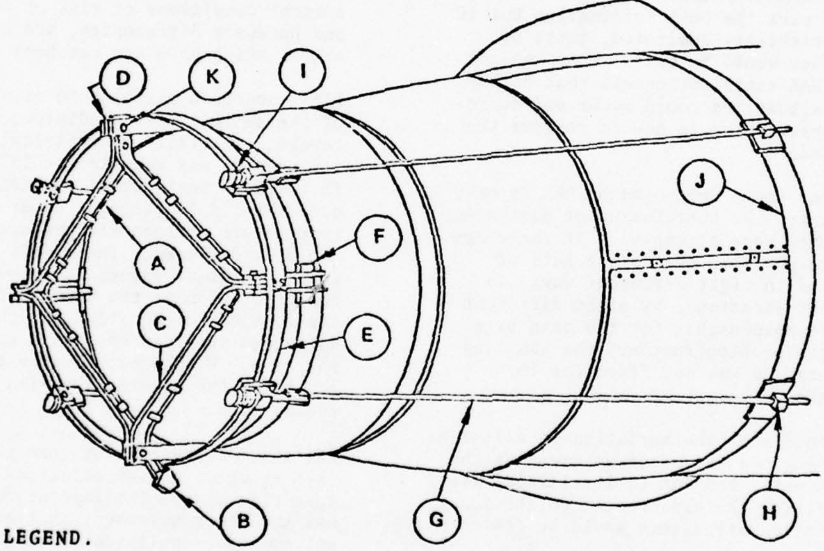


FIGURE 2. SAMPLING PROBE DESIGN CONFIGURATION



LEGEND.

A. Probe Tube
B: Probe Outlet Manifold
C. Probe Back-Up Structure
D. Probe Mount Clevis
E. Torsional Support Ring
F. Clevis Mount Pad
G. Tensioning Rod
H. Tensioning Rod Adjusting Nut
I. Thermal Expansion Spring
J. Reverser Forward Shroud
K. Probe Attach Bolts

FICURE 3. TYPICAL ENGINE INSTALLATION OF FEDERAL AVIATION ADMINISTRATION SAMPLING RAKE PROBE

TABLE II -- PRESSURE, TEMPERATURE, AND HUMIDITY CORRELATING PARAMETERS FOR TURBINE ENGINE EXHAUST EMISSIONS

ENGINE TYPE	CORRELATING PARAMETERS HYDROCARBONS	CORRELATING PARAMETERS OXIDES OF NITROGEN	CORRELATING PARAMETERS CARBON MONOXIDE	
JT8D-9	$P_b^{0.75}\sqrt{T_b} \cdot e^{T_b/(500 - F/A \cdot 10^4)}$	$P_b^{0.5} \cdot e^{T_b/725} / e^{19H}$	$P_b^{0.75}\sqrt{T_b} \cdot e^{T_b/B}$	$B = (400 - F/A \cdot 10^4)$ $B = 315$ Idle
JT8D-7	$P_b^{0.75}\sqrt{T_b} \cdot e^{T_b/(400 - F/A \cdot 10^4)}$	$P_b^{0.5} \cdot e^{T_b/500} / e^{19H}$	$P_b^{0.75}\sqrt{T_b} \cdot e^{T_b/B}$	$B = (400 - F/A \cdot 10^4)$ $B = 330$ Idle
JT3D-3B	$P_b^{1.8}\sqrt{T_b} \cdot e^{T_b/140}$	$P_b^{0.5} \cdot e^{T_b/675} / e^{19H}$	$P_b^{0.75}\sqrt{T_b} \cdot e^{T_b/B}$	$B = (400 - F/A \cdot 10^4)$
JT3D-7	$P_b^{1.8}\sqrt{T_b} \cdot e^{T_b/140}$	$P_b^{0.5} \cdot e^{T_b/600} / e^{19H}$	$P_b^{0.75}\sqrt{T_b} \cdot e^{T_b/B}$	$B = (400 - F/A \cdot 10^4)$
JT9D-3A	$P_b^{1.8}\sqrt{T_b} \cdot e^{T_b/240}$	$P_b^{0.5} \cdot e^{T_b/225} / e^{19H}$	$P_b^{0.75}\sqrt{T_b} \cdot e^{T_b/B}$	$B = (400 - F/A \cdot 10^4)$
CF700	$P_b^{1.8}\sqrt{T_b} \cdot e^{T_b/475}$	$P_b^{0.5} \cdot e^{T_b/600} / e^{19H}$	$P_b^{0.75}\sqrt{T_b} \cdot e^{T_b/B}$	$B = (600 - F/A \cdot 10^4)$ $B = 500$ Idle
RB211	$P_b^{1.8}\sqrt{T_b} \cdot e^{T_b/450}$	$P_b^{0.5} \cdot e^{T_b/275} / e^{19H}$	$P_b^{0.75}\sqrt{T_b} \cdot e^{T_b/B}$	$B = (525 - F/A \cdot 10^4)$ $B = (600 - F/A \cdot 10^4)$ Idle and Approach

FAA therefore, under the sponsorship of the Coordinating Research Council (CRC), has accepted the task of cross-correlating results from these various sets of equipment. At the FAA facility near Atlantic City, New Jersey, an engine will be operated with multiple sets of these units, all sampling a common repeatable source. The results from any unit can be compared with any other unit. This effort will give both industry and government a degree of comfort and confidence that each system is relatable to a set value.

The most important work, however, is the actual documentation of what variability exists between engines of like manufacture. This information will give FAA the necessary data to establish the sample size for emissions acceptability for certification purposes.

FAA is presently negotiating contracts to collect actual test data from new production engines manufactured by General Electric (G.E.) and Rolls-Royce. Some data on Pratt and Whitney Aircraft (P&WA) engines has already been received.

The data received from P&WA is disturbing to FAA in that the variability seen between like engines is large. Table III shows the degree of variability present. The raw data has been adjusted for varying ambient conditions using factors developed by NREC. Because of the large spread, FAA also used internally-developed P&WA ambient correction factors on the data to determine if the variability could be a function of the NREC factors. Unfortunately, the result was not changed, indicating that the ambient corrections were proper or at least were not distorting the data.

The information FAA hopes to obtain on the G.E. and Rolls-Royce engines in late 1978 and early 1979 will be examined to establish what spread is exhibited. If results are similar to the P&WA information, FAA's desire to require tests on only a few engines of each type may not be adequate for certification purposes. The data indicates that until a good statistical data set is hand, considerable numbers of engines will have to be examined.

Earlier an effort to determine the effect of operating time upon emissions was mentioned. That effort involved collection of data from seven different types of engines. Approximately 15 to 20 engines of a given type were examined at intervals of 600 hours over an elapsed time of 3000 hours per engine.

In the course of this investigation which was performed over the period 1974 to 1978 by Northern Research and Engineering Corporation (NREC) under contract to the FAA, a totally analytical approach to the question of ambient correction factors was undertaken. The results of this work confirmed the empirical expressions developed earlier. An illustration of the agreement is shown in Figure 4 which compares the NREC factors to FAA empirical factors. The mathematical expressions are shown in Table II.

Having reached a point where the understanding of the sampling techniques, and correction factors can influence the result, the FAA turned to the present equipment in use.

Over the past five or so years, much interchange of information relative to the sampling equipment and its proper usage has produced, within each users organization, a fairly good level of confidence concerning how accurate and/or repeatable are the results emanating from the system.

Figure 4b. Comparison of Ambient Corrections for JT8D-7 HC Emissions Data

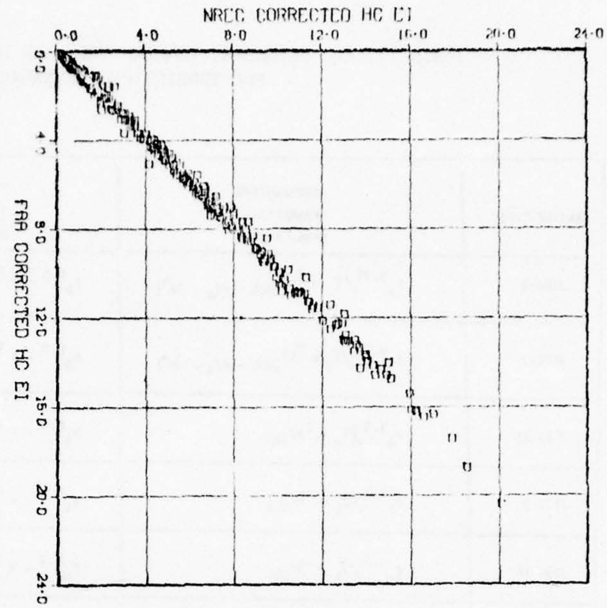


Figure 4a. Comparison of Ambient Corrections for JT8D-7 CO Emissions Data

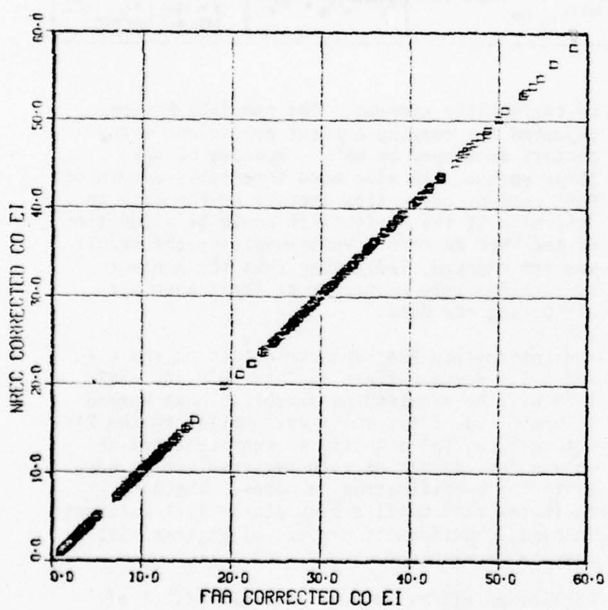


Figure 4c. Comparison of Ambient Corrections for JT8D-7 NO Emissions Data

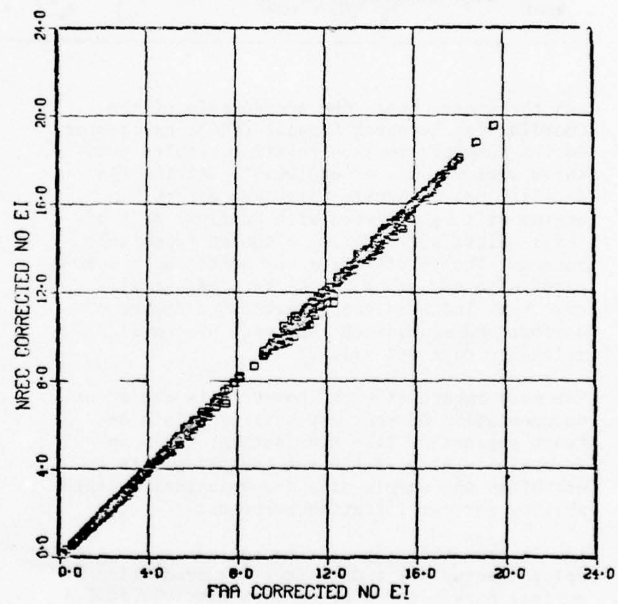


TABLE III -- VARIABILITY OF PRATT AND WHITNEY AIRCRAFT TURBINE ENGINE EXHAUST EMISSIONS

ENGINE TYPE (COMBUSTOR MODEL)	CARBON MONOXIDE, CO gm/Kn	UNBURNED HYDROCARBONS, THC gm/Kn	OXIDES OF NITROGEN, NO_x gm/Kn
JT8D-9 (40-17A)	112.42 - 152.75	25.09 - 90.00	38.93 - 60.11
JT8D-17 (46-2N)	97.24 - 130.42	17.17 - 58.20	44.82 - 78.28
JT9D-7A (73-16E)	137.56 - 163.15	51.78 - 75.37	48.39 - 58.39
JT9D-7F (73-46G)	84.63 - 98.67	* - *	59.08 - 66.80
JT9D-7F (73-53J)	86.28 - 106.30	* - 45.61	63.46 - 70.84

* Insufficient Data

NOTE: The range of values in each case, represents the extremes of the data resulting when all engines of a like model are compared to each other.

The data from this work has just been released.[7] The analysis of whether measurable or significant changes in emissions occurred is a separate study and will be released within three months. At this time emissions of NO_x appear to show a decrease of approximately five percent over a 1000 hour time period.

Changes in emissions of carbon monoxide, unburned hydrocarbons, and smoke are being examined but the analysis is too preliminary to allow statements of what changes are seen.

The future activities of FAA in the emissions arena are primarily aimed at defining the average emission level of engine types. A constant comparison of emission trends versus engine type is being maintained to recognize and document similarities that may allow acceptance of fewer sets of data for use in certification tests. It is expected the bulk of the R&D necessary to establish the adequate data base will be in-hand by late 1979.

SUMMARY

1. FAA R&D activities have been devoted to development, refinement, and standardization of the equipment, procedures, and analyses techniques for emission tests. These instrumentation and analyses techniques are now considered acceptable and accurate.

2. The initial major concern over temperature pressure and humidity correction factors has been eased. Adequate procedures have been developed.

3. Cross-correlation of results of industry and government emission sampling systems will be completed by mid-1979.

4. Documentation of the inherent variability of engines is partially complete and should be complete by the end of 1979. The overall picture is that the variability is large--to an extent that it may be unreasonable to expect all engines to be in full compliance.

5. New technology in combustors shows promise in reducing emissions. Incorporation into the active fleet is beyond the time remaining before implementation of EPA requirements.

6. The safety aspects of the new technology are largely unknown. A major effort in this area must be addressed.

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AIRCRAFT NOISE RESEARCH

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BIOGRAPHY

Robert S. Zuckerman is the Program Manager of the Federal Aviation Administration (FAA) Aircraft Noise Research Program. He received a B.M.E. from City College of New York (C.C.N.Y.) in 1952, an M.S. in Management Engineering from Long Island University (L.I.U.) in 1967 and an M.S. in Operations Research in 1970 from the Polytechnic Institute of Brooklyn (now Polytechnic of New York). He earned the L.I.U. 1967 Graduate Management Engineering Department Prize for Outstanding Scholarship. Before joining FAA in 1971, he spent seven years with the National Aeronautics and Space Administration (NASA) on the Apollo Program as a member of the Lunar Module Resident Program Management Team where he served as a Subsystem Manager, a Systems Engineer and finally as Vehicle Manager for Lunar Module LM-3. Mr. Zuckerman has been involved in aerospace vibration, acoustics and structural dynamics engineering with several aerospace firms; has been an adjunct faculty member at C.C.N.Y. and L.I.U. and is a licensed Professional Engineer (New York 1957; Maryland 1974).

ABSTRACT

The abatement of aircraft noise was an FAA goal before enabling legislation provided regulatory authority. The current FAA aircraft noise research is discussed, with emphasis on the JT8D Mixer Demonstration project and the "High Velocity Jet Noise" project. The JT3D and JT8D Nacelle Retrofit programs as well as the Core Engine Noise and Combustion Noise Investigations are included. An extensive listing of FAA-sponsored research reports is included, as well as milestones for completion of existing projects and the projected benefit of each project. Completed projects, including sonic boom investigations and human response investigations which supported the choice of the Effective Perceived Noise Level (EPNL) are briefly discussed and referenced.

BACKGROUND

Aircraft noise and sonic boom are currently critical constraints on the growth of civil aviation.[1] During the past decade there have developed an increasing number of complaints about noise in the vicinity of airports. The problem has increased with the steady increase in frequency of operations and urban encroachment around airports. Community objection to aircraft noise has brought on airport restrictions involving night curfews, aircraft type (power plant, number of engines, gross weight, etc.), preferential runway usage, and limitations on expansion of existing airports. Construction of new airports has been blocked. Airport operators have imposed restrictions on aircraft operators which ban noisier aircraft. Newly designed airports which have utilized enormous land areas and remote sites which reduce convenience have not been universally successful in reducing community complaints in accordance with design predictions. Current airport projections show no new major airports planned for construction within the next decade.

The responsibility and authority of the FAA for control and abatement of aircraft noise and sonic boom is defined by law. On July 21, 1968, Public Law 90-411 was enacted by the Congress. This law amends the Federal Aviation Act of 1958 to require noise abatement regulation. Its purpose is to provide statutory authority for the control and abatement of aircraft noise and sonic boom. It directs the Administrator of the FAA, in consultation with the Secretary of Transportation, to prescribe and amend standards for the measurement of aircraft noise and sonic boom, and it includes the application of such standards, rules and regulations in the issuances, amendment, modification, suspension or revocation of any certificate authorized by Title VI of the Federal Aviation Act.[1]

In describing the current status of the FAA's Research and Development (R&D) Program, it is useful to quote the Notice of Proposed Rulemaking (NPRM 75-37), sometimes called the Federal Aviation Regulation Part 36 (FAR Part 36) minus X,Y,Z, which states: "In order to fulfill its commitment to its aircraft noise control and abatement program, the FAA intends to continu-

ously monitor and periodically review the state-of-the-art, determining whether further amendment of standards or procedures is appropriate".

The FAA's R&D role and responsibility is directly related to regulatory support by a program planned to provide a data base from which to develop rulemaking, measurement, certification, and compliance techniques for control and abatement of aircraft noise. A data base must be provided for all categories of aircraft that assures aircraft noise regulations that are economically reasonable, technologically practicable and appropriate to the aircraft type.[2] The process of producing the data base will provide a positive force for action both in spurring the regulatory process and by demonstrating to industry that technology growth will not be absorbed by improved performance, without regard for the environment.

General objectives are to minimize the environmental impact of aircraft noise and develop prediction, reduction and certification criteria for all classes of aircraft. Specific objectives are to:

1. Develop acceptable yardsticks for evaluating effects of level and quality, of aircraft noise on man.

2. Develop economically acceptable retrofit programs to minimize current aircraft noise levels.

3. Determine the mechanisms of noise and shockwave generation and develop methods of reduction at the source for application to next generation aircraft.

4. Determine effects of operational procedures, atmospheric and ground attenuation on transmission of aircraft noise.

5. Investigate parameters that influence aircraft noise effects on man.

PRODUCTS/EXPECTED RESULTS

The Aircraft Noise Research and Development Program is intended to provide a technology base from which to develop rule making for control and abatement of aircraft noise. During this decade projects have been conducted in four areas; aircraft source noise reduction, operational noise reduction, aircraft noise evaluation and response, and sonic boom.

Source Noise Reduction Retrofit Feasibility - A major project begun in the early 1970's was an investigation of the feasibility of retrofitting the older turbofan powered commercial jet fleet. The aircraft considered were the B-707, and DC-8's powered by JT3D engines and B-727, B-737, and DC-9's powered by JT8D engines. Sound absorption treatment of the engine nacelles was evaluated during ground and flight tests.[3-6] Additional efforts at quieting involving exhaust suppressors and other engine exhaust system modifications were evaluated. Noise reduction feasibility for business jet aircraft was also investigated.[6]

Jet Noise Suppression - Two projects are included in the jet noise reduction effort. The first, "High Velocity Jet Noise - Source Location and Reduction" was aimed at gaining a fundamental understanding of jet noise suppression mechanisms. Both theoretical and experimental work was included, with emphasis placed on in-flight suppression. A general suppressor scaling and methodology was to be developed, resulting in a suppressor nozzle design guide. The project was divided into six tasks, three of which are completed.[7] The remaining tasks, for which reports will be completed and published during the current year, are as follows:

TASK 3 - "Experimental Investigation of Suppression Principles"

TASK 5 - "Investigation of 'In-Flight' Aeroacoustic Effects"

TASK 6 - "Noise Abatement Nozzle Design Guide"

An additional task, extension of the prediction model to cover flow mixers is planned to be undertaken in Fiscal Year 1979 and completed in 1980.

The second project covers application of existing technology toward development of a technologically practicable and economically reasonable jet noise suppressor for the JT8D engine. This suppressor concept involves mixing of the fan air flow with the core engine flow, upstream of the jet nozzle. Model tests[8] of this internal flow mixer indicate a noise reduction of 4 PNdB and a reduction in cruise specific fuel consumption of 1 percent. Full-scale ground tests are currently underway, with flight testing planned for the spring of 1979. All reporting is scheduled for publication by the end of 1979.

Core Engine Component Noise Evaluation and Control - The purpose of this project was to provide theoretical and experimental data to assist the designers in developing future technology aircraft capable of conforming to lower noise levels than were required by FAR Part 36, while meeting stringent emissions level requirements imposed by the Environmental Protection Agency (EPA). The effort was directed to identifying, evaluating, and controlling[9,10,11] the component noise sources inherent in the

core engine (the gas generator) which, in composite, now forms the approach noise floor.

Current effort, which will be completed during 1978, is a modest attempt to account for effects such as entropy noise and vorticity effects.

Aircraft Configuration Effects - The purpose of this two fold project was first to study the feasibility of and develop prediction procedures applicable to the practical use of aircraft configuration shielding surfaces and engine placement to reduce engine noise propagation to the ground.[12] The second was to develop a noise prediction and reduction data base for airframe aerodynamic noise sufficient to support the baseline definition for approach noise regulations.[13]

Helicopter/STOL Aircraft Noise Prediction and Reduction - The short haul potential of these vehicles will not be realized until environmental constraints are satisfied. The lift systems for STOL and helicopters craft are distinctly different from conventional aircraft designs. The wide range of still undefined designs allows the potential for widely different, unique noise characteristics. Prediction models for jet powered lift configurations[14,15,16] and for rotary propulsors[17] (including helicopter rotors) have been developed. Frequent updating and improvement of the prediction models is essential to their usefulness. Current effort, expected to be completed during 1978, involves addition of forward flight[18,19] effects to the existing V/STOL Rotary Propulsors Model, based on flight data obtained by FAA.[20]

Operational Noise Reduction - The product and expected benefit of the FAA's operational investigation of aircraft noise abatement is improvement and refinement of noise certification procedures and community noise exposure estimates. The objective of the noise propagation and measurement project and the noise certification measurement and analysis project is definition of the significant factors which affect the transmission of aircraft noise from the source to the receiver.

Noise Propagation and Measurement - This project includes studies[21-24] of the effects of atmospheric temperature, humidity, wind and turbulence on aircraft noise propagation. Understanding propagation effects will also permit a reduction in flyover noise measurement variability by means of appropriate correction factors.[25] The estimation of the community noise exposure areas is necessary before meaningful Noise Exposure Forecast contours can be generated.[26] Work will continue on improving measurement techniques and ground effects by use of an FAA aircraft noise measurement facility at the National Aviation Facilities Experimental Center (NAFEC), the FAA experimental center. These improvements will make use of the FAA's Integrated Noise Model[1] increasingly valuable.

Noise Certification Measurement and Analysis - The development of noise certification procedures currently specified by FAR Part 36, Appendices C and F are objectives of this project. Substantial data has been developed[27-51] and used for certification improvement. The use of the NAFEC Aircraft Noise Measurement Range will support a continuing effort and products.

TECHNICAL APPROACH

FAA Demonstration Programs - The FAA's nacelle retrofit feasibility program[3,4,5,52] invesigated the noise reduction benefit provided by sound absorbing material in the inlet, engine and discharge passages. It also investigated, as a higher risk goal, the benefit provided by then-available jet noise suppression technology, from exit area modification to complex ejector-suppressor designs. The lower goal designs, utilizing sound absorbing lining, substantially reduced the fan tones and broadband noise, providing very substantial noise reductions, measured during the approach phase of aircraft operation (Figure 1). Typical results showed reductions on the order of 6 dB for the JT8D powered B-727/200 and 14 dB for the JT3D-powered B-707/300. For the takeoff/cutback phase the reductions were about 2 dB for JT8D powered aircraft and about 11 dB for the JT3D-powered aircraft. (Figure 2) The use of then-current jet noise suppression technology did not appear reasonable because of excessive cost, weight, and performance degradation.

The FAA/JT8D mixer project is a logical, long-awaited application of technology for jet noise reduction. Use of an internal mixer for reduction in fuel consumption during cruise mode has been predicted since the first turbofan engine design. (Figure 3) Technology has now been developed[8,28,53] which yields the potential for the development of a fuel conservative, light-weight, bolt-on engine part which can be installed in new production and existing JT8D-powered aircraft. The mixer should be used in combination with sound absorbing nacelle and engine treatment to reduce fan noise and jet noise. Expected benefits are jet noise reductions at the takeoff and sideline measuring points of 4 dB. (Figure 4) When noise contours[28] are considered, the expected benefit is a 50 percent reduction in the area encompassed by specific contours, such as 90 EPNdB or 100 EPNdB. Another potential benefit includes reduction of shock noise applicable to engine cycles with higher engine pressure ratios. The expected reduction in fuel usage because of increased cruise thrust performance (1 percent expected) will be increasingly im-

important as the cost of all forms of non-renewable fossil energy continues to grow.

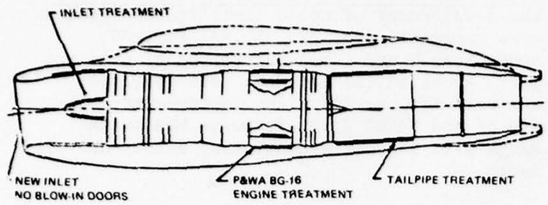
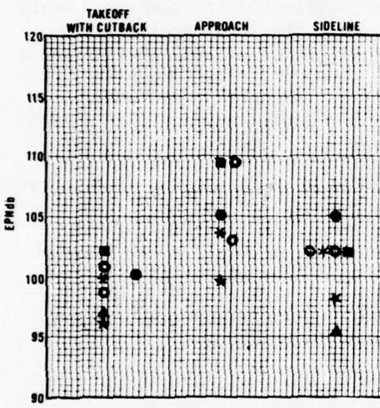


FIGURE 1. FAA RETROFIT FEASIBILITY B-737 QUIET NACELLE



PERFORMANCE RESULT (727/200)		
Element Changed	SAM Only	SAM + JET
Fuel Increase	≈ 0	3% to 8%
Runway Increase	≈ 0	600
Range Decrease	≈ 0	275
Weight Increase	395	2,700

FIGURE 2. JT8D/B-727-200 RETROFIT FEASIBILITY RESULTS

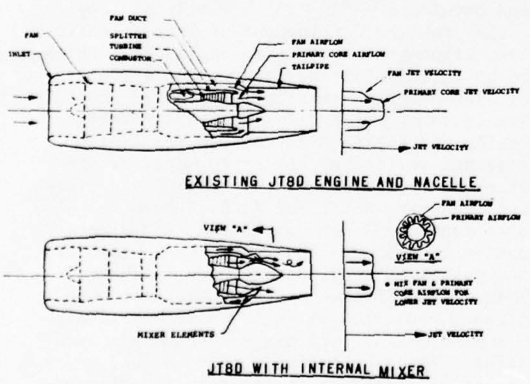


FIGURE 3. INTERNAL MIXER FOR JT8D ENGINE

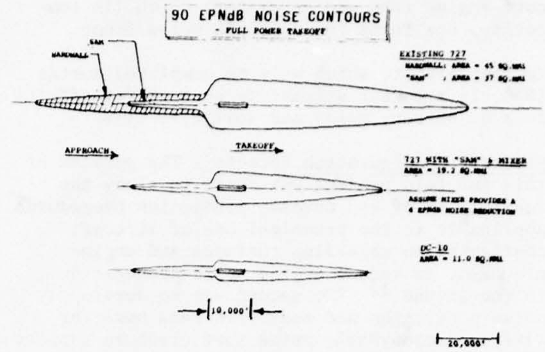


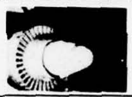
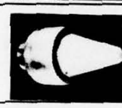
FIGURE 4. FAA/JT8D MIXER--NOISE CONTOURS

High Velocity Jet Noise Suppression - A legacy of noise abatement technology[54-57] was left by the FAA's supersonic transport development program. The Supersonic Transport Program Phase I and Phase II follow-on efforts produced model suppressor nozzle designs and static test data. The multitube and multichute nozzles of various radius-ratios and area-ratios provided a wealth of information, but the key to understanding jet noise and effective suppression in flight, without crippling performance losses, required additional effort.

The "High Velocity Jet Noise Source Location and Reduction"[7] program was intended to avoid the shortcomings of over two decades of research which failed to achieve their goals because of an inadequate span and inadequate resources, including facilities, time and dollars. The effect of flight as well as understanding the fundamental nature of noise sources were among the highly ambitious goals. Other goals involved less risk, but required substantial resources. These included: the activation of facilities for experimental evaluation, the development of laser velocimetry and other source location techniques, the development of techniques for in-flight evaluation of jet noise and finally the testing of many types of multichute, multispoke and coannular nozzles under static and simulated flight conditions. Results from testing optimum suppressor nozzle designs shown in Figure 5 clearly illustrate the need for in-flight simulation of acoustic results and performance.

This DOT/FAA program has come close to the goal of developing a fundamental understanding of jet noise, including in-flight effects. Prediction models developed by the contractor, the General Electric Company (G.E.) applicable to axisymmetric nozzles, including coannular, multispoke and multichute nozzles can be used to provide an analytic tool to optimize and synthesize a suppressor nozzle system. The

FIGURE 5. OPTIMUM SUPPRESSOR NOZZLE DESIGNS

				VMA CONICAL 1600-2500 FPS	ALL Δ S RELATIVE TO CONICAL NOZZLE	
MODEL NO	CONFIGURATION	SCHEMATIC	PHOTOGRAPH	VMA RANGE (MASS AVERAGED IDEAL MIXED FLOW)	PEAK SUPPRESSION ΔPNL AT AIRCRAFT VELOCITY = 275 FT/SEC (FREE JET DATA SCALED TO J79 SIZE)	ΔC_{FG} LOSS NOZZLE COEFF AT $M \approx 0.36$
1	32 CHUTE AR = 2.0			2000-2300 FEET/SEC STATIC	13-13.5 PNdB	~2.5%
				2100-2500 FEET/SEC FREE JET IN-FLIGHT SIMULATION	12-13 PNdB	~6.2%
2	40 SHALLOW CHUTE AR = 1.75			1700-2075 FEET/SEC STATIC	12-12.5 PNdB	~7.2%
				1900-2500 FREE JET IN-FLIGHT SIMULATION	10-11 PNdB	~9.0%
3	36 CHUTE AR = 2.0			1800-2125 FEET/SEC STATIC	12-12.5 PNdB	~2.8%
				2050-2250 FREE JET IN-FLIGHT SIMULATION	11-12 PNdB	~4.1%
4	36 CHUTE WITH TREATED EJECTOR AR = 2.0			1875-2125 FEET/SEC STATIC	12-13 PNdB	~1.5%
				2025-2250 FREE JET IN-FLIGHT SIMULATION	11.5-12.5 PNdB	~4.5%
5	54 ELEMENT COPLANAR MIXER			1250-1750 FEET/SEC STATIC	~8.0 PNdB	~3.5%
				1000-1800 FREE JET IN-FLIGHT SIMULATION	7-7.5 PNdB	~3.2%

Task 6 final report will be a suppressor nozzle design guide which will include an engineering correlation method for suppressor nozzle system design, which will provide weight, performance and suppression estimates.

The analytical and experimental portion of this jet noise research program are complete. The submittal of all draft final reports, including the Task 6 Jet Noise Suppressor Nozzle Design Guide will be completed within 1978. The extension of the theoretically derived jet noise prediction model to mixer nozzles will be accomplished by the newly defined Task 7. The unified aeroacoustic jet noise prediction model must be modified to deal with lower velocity jets with internal mixer nozzles, applicable to subsonic transport bypass engines, as well as high velocity jet engine applications. (Figure 6)

Propulsion Noise--High Bypass Turbofan Technology - The high bypass turbofan avoided the use of high jet velocities by increasing the mass flow, compared to the earlier low-bypass ratio engines. Fan noise reduction technology, by means of acoustic lining revealed the existance of noise sources from the core engine or gas generator which prevented writing regulations requiring lower noise levels based on fan noise and jet noise alone. The JT8D-209 (NASA Refan Engine Derivative) noise reductions are limited by core engine noise at the takeoff/cutback condition.

The FAA initiated the Core Engine Noise Evaluation and Control Program in 1972. The objective was to identify and evaluate core engine component noise sources in order to develop means of control. The original contract effort was completed in 1974. Phase 1 of the contract completed an identification and rank ordering of significant noise sources, including: jet exhaust stream, turbine, combustor, obstructions in flow passages, fan/core exhaust stream interaction, casing radiation, etc. Phase 2 and 3 developed theoretical or empirical mechanisms of noise generation and suppression. The development of prediction techniques during the final phase of the contract provided the tools both for aircraft design and the data base for new technology projections.

In 1975, the emergence of low-emissions combustor designs, for which noise data was limited and where substantial configurational differences existed between G.E. and Pratt and Whitney Aircraft (P&WA) designs, prompted the investigation of the noise characteristics of low emissions combustors by both engine manufacturers[10,11] differences between prediction models existed, but these reflected different design philosophies. At an FAA sponsored Jet Noise/Core Noise Status Review meeting during February 1977, it was proposed that after other factors, such as high temperature gas spots (entropy spots) and combustor vorticity effects were considered, the investigation of combustor noise would be adequate.[58] The experimental investigation of entropy and vorticity effects by Georgia Institute of Technology is expected to complete the FAA's need for a composite model of combustion noise. This effort should be completed during 1978.

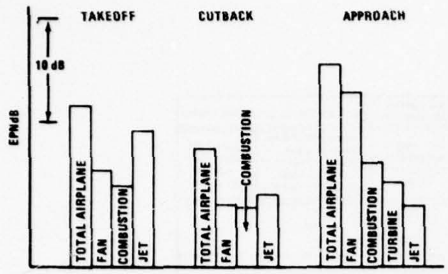


FIG. 6. NOISE COMPONENT ANALYSIS FOR JT8D-209 IN NARROW-BODYED AIRCRAFT.

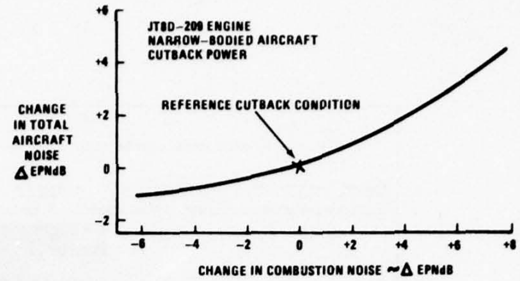


FIG. 7. TOTAL AIRCRAFT NOISE VERSUS COMBUSTION NOISE CHANGE-JT8D-209

Certification Refinement--Atmospheric Attenuation and Ground Effects - Development of effective regulations which defy circumvention without costly restrictions on test site and weather restrictions requires an iterative approach. When attempts to escape regulatory intent occur, the technicality used may be eliminated by providing an improved data base which can lead to more effective certification rules.

Certification and noise measurement research work is being continued chiefly by in-house engineering plus occasional small contract support. Flight Tests recently were conducted and reported on the effect of variations in air temperature and humidity along the noise propagation path during certification testing.[24] These results have been applied to improve noise certification accuracy by the FAA regulatory office. Work has been completed for refinement of certification procedures for general aviation aircraft. A study of noise measurement[25] systems is complete. A project involving refinement of procedures for development of noise exposure contours is planned in addition to continued certification research. Flight tests to study effects of wind and turbulence on noise certification measurements are also planned.

Recent noise evaluation and human response work has covered certification criteria for helicopter and STOL aircraft plus psychoacoustic tests to better understand response to both single and multiple events of conventional aircraft. Current projects include better definition of acceptable noise levels and airport community noise exposure level goals.

Noise Evaluation and Human Response -- The development of acceptable yardsticks for evaluating the effects of level and quality of aircraft noise on man is the product and expected benefit of this program element. Early efforts led to development of EPNL, used in Far 36. A continuing effort is underway to expand and improve a substantial body of data developed by FAA[33-35] and others. Annoyance criteria for advanced aircraft, such as STOLcraft and SST craft[37,38] is needed. Efforts to improve understanding of helicopter noise[39,20] are continually in progress.[40-46] The search for refined measures may provide a simpler methods of measuring noise impact[43] or merely improvement for a limited scope. All work in progress will be completed in 1979 or earlier.

Sonic Boom -- Sonic Boom research was reduced to a minimal effort, such as Concorde Boom Monitoring, due to passage of FAR Part 95.1, which prohibits civil aircraft operation over the United States at true flight speeds greater than Mach 1.0, to prevent any sonic booms from reaching the ground. A substantial body of knowledge is available, applicable to sonic boom in general and boomless supersonic flight in particular.[44-57] No further activity in sonic boom research is planned or expected at this time.

SUMMARY

The FAA Noise Abatement Research Program in support of regulation has produced benefits for the National Air Transportation System. Although expenditures are heavily weighted towards Source Noise Prediction and Reduction, improving certification by means of atmospheric propagation studies and examination of noise evalua tion yardsticks, must continue to be supported. The current JT8D Mixer Demonstration Program has the greatest potential for reducing fleet noise impact, assuming that the application proves cost-effective, as well as energy and environment-effective. Research and technology projects including Jet Noise Suppression and High Bypass Technology will continue, but noise reductions will be more difficult to achieve than the reductions.

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CRASHWORTHINESS

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Biography

Herbert C. Spicer, Jr. is a program manager in the Aircraft Design Criteria Branch. He received his B.S. in aeronautical engineering in 1951 from the University of Maryland. Prior to joining the FAA in 1959, he spent 5 years as a loads-stress engineer at Lockheed, two years as structural loads engineer at the Bureau of Aeronautics and two years as a design evaluation engineer at the Civil Aeronautics Board. Mr. Spicer has held several positions in the FAA Flight Standards Service and Systems Research and Development Service.

ABSTRACT

The agency's crashworthiness program was initiated with the general aviation airplane in an effort to increase the probability of survivability and to minimize the possibility of serious injuries. Three efforts were undertaken. The first was with regard to the seat/occupant/restraint system; the second with regard to the basic airplane structure and the third with regard to demonstrating the feasibility of applying modified U.S. Army crash resistant fuel system technology.

Two mathematical simulation models were developed. The first, Program SOMLA, was to simulate the dynamic response of the seat/occupant/restraint to any dynamic crash impact pulse. The other, Program KRASH, an extension of a U. S. Army program, was to simulate the dynamic response of the airplane structure to crash impact conditions. Developmental tests of simplified seats show the need to represent better seat leg and neck response. These tests are continuing and production seat tests will follow in the next fiscal year. Four full-scale crash tests were conducted at NASA-Langley Research Center to verify Program KRASH. Test results and computer predictions of failures, times of occurrence during the crash sequence and accelerations were good.

Crash resistant fuel system in full-scale crash tests using 12½ single-ply tank material and light-weight self-closing valves survived 63 mph impacts into poles and rocks without damage or fuel spillage. The eight ounce and five and one -half ounce materials ruptured under the test conditions. Future applications to helicopter and transports are briefly discussed.

BACKGROUND

General aviation airplanes (175,000) now carry over 90 million people annually and operate out of all the nations 13,733 airports. General aviation airplanes have been proven to be competitive with other forms of transportation and it is expected that the industries' growth rate will continue to increase. Accidents occur and compared in terms of passenger miles the fatality rate is at least 10 times greater than the automobile and 100 times greater than the airlines, trains and buses according to the National Safety Council. In terms of specific numbers, general aviation airplanes are involved in about 4500 accidents each year, of which about 700 result in fatalities. In these fatal accidents, about 1400 people are killed every year. An increasing effort is evident to reduce the number of persons killed or injured in vehicular accidents. To this end, the agency has undertaken a program with the following objectives:

1. Develop computerized mathematical simulation models which can predict the dynamic response of airplane structure and seat/occupant/restraint system.
2. Verify these models with full-scale testing.
3. Demonstrate crash resistant fuel system technology applicable to the general aviation airplane.
4. Establish the basis for design criteria.
5. Expand the technology to helicopters and transport airplanes.

PRODUCTS EXPECTED

1. Basic Theory Reports

   a. FAA-RD-74-130, "Development of a Scientific Basis for Analysis of Aircraft Seating Systems, January 1975.

   b. FAA-RD-76-123, "A Method of Analysis for General Aviation Airplane Structural Crashworthiness, September 1976.

2. User's Manuals

   a. FAA-RD-77-189, "General Aviation Airplane Structural Crashworthiness User's Manual, February 1978.

      . Vol. I - Program "KRASH" Theory

      . Vol. II - Input-Output Techniques and Applications

      . Vol. III - Related Design Information

3. Programmer's Manuals

4. Test Verification Reports

   a. FAA-RD-77-188, "Full-Scale Crash Test Experimental Verification of a Method of Analysis for General Aviation Airplane Structural Crashworthiness, February 1978.

   b. FAA-RD-78-28, "Interim Report - Tests of Crash Resistant Fuel Systems for General Aviation Aircraft, March 1978.

5. Workshop - Seminars

6. Proposed Crash Environment Criteria

TECHNICAL APPROACH

General

These efforts were undertaken through competitive bidding. Where applicable, state-of-the-art technology served as the basis for our programs; in particular, the work of the U. S. Army. Other groups within the FAA (NAFEC and CAMI), NASA-Langley Research Center, U. S. Army-Eustis Directorate, Naval Research Laboratory and the General Aviation Manufacturers Association have been active participants.

Seat/Occupant/Restraint

Several one, two and three-dimensional mathematical models of the human body have been developed for crash survivability analysis of automobile accidents (Ref. 1, 2 and 3). Seat representations used with these automotive human body models were very simple, because the role of the seat in determining automobile occupant survivability was minimal. In the case of the general aviation airplanes, not only are longitudinal forces important but vertical forces are equally important and lateral forces are important to a lesser degree. Building a strong seat is not the answer, since such a seat would not only transmit impact forces directly to the occupant but would also produce serious weight penalties. In order to fulfill the needs of the agency and to provide a verified analytical tool for crashworthy design, a program was undertaken to develop a user oriented computer program SOMLA that simulates the dynamic response of a single seat, occupant and restraint system to a crash environment. Competitive bidding procedures were used and the basic program was awarded to Dynamic Science. Follow-on work has been continued with the Pennsylvania State University.

Figure 1 shows a typical occupant model. Body element weights are lumped at their mass center. Joints are represented with appropriate rotational resistance and typical rotational degrees of freedom. Body contours are represented by ellipsoids and cylinders. Any restraint system can be represented; seat belt only, seat belt with single or double chest restraint, and a crotch strap.

The seat is represented by beam and membrane elements in a generalized form to include fixed and adjustable seats and energy absorption (also Figure 1).

Cabin interior surfaces are approximated for occupant contact analysis. Several injury criteria are included; such as, the DRI (Dynamic Response Index) for vertical acceleration parallel to the spine; SI (Severity Index) for impacts of the body with structure; and HIC (Head Injury Criteria) for injury due to accelerations.

The basic theory has been developed. Static tests of production seats have been completed at NAFEC. Dynamic tests of simple seats will be completed this fiscal year at CAMI and production seats next fiscal year. The results to date show a need to improve the representation of the occupant neck and the seat leg in Program SOMLA to obtain a better correlation with test results. These changes are being made.

Airplane Structure

A number of computer mathematical analysis models had been developed which, within strict limits, could evaluate the structural response of components of structure. Only one model has

Figure 1 -

THREE DIMENSIONAL SEAT-OCCUPANT COMPUTER MODEL

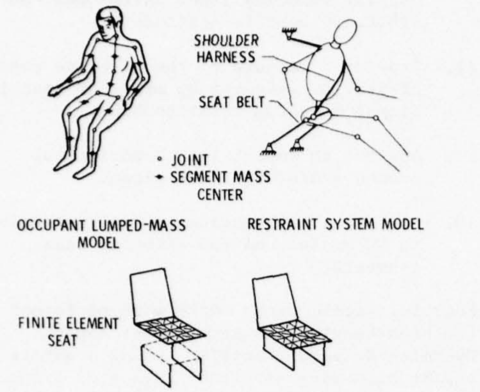


Figure 2 - Lumped Mass Model of Airplane

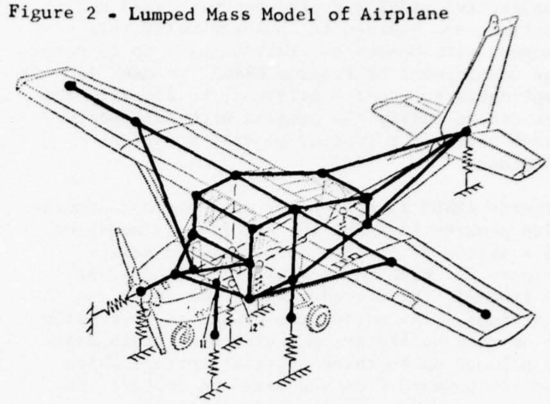
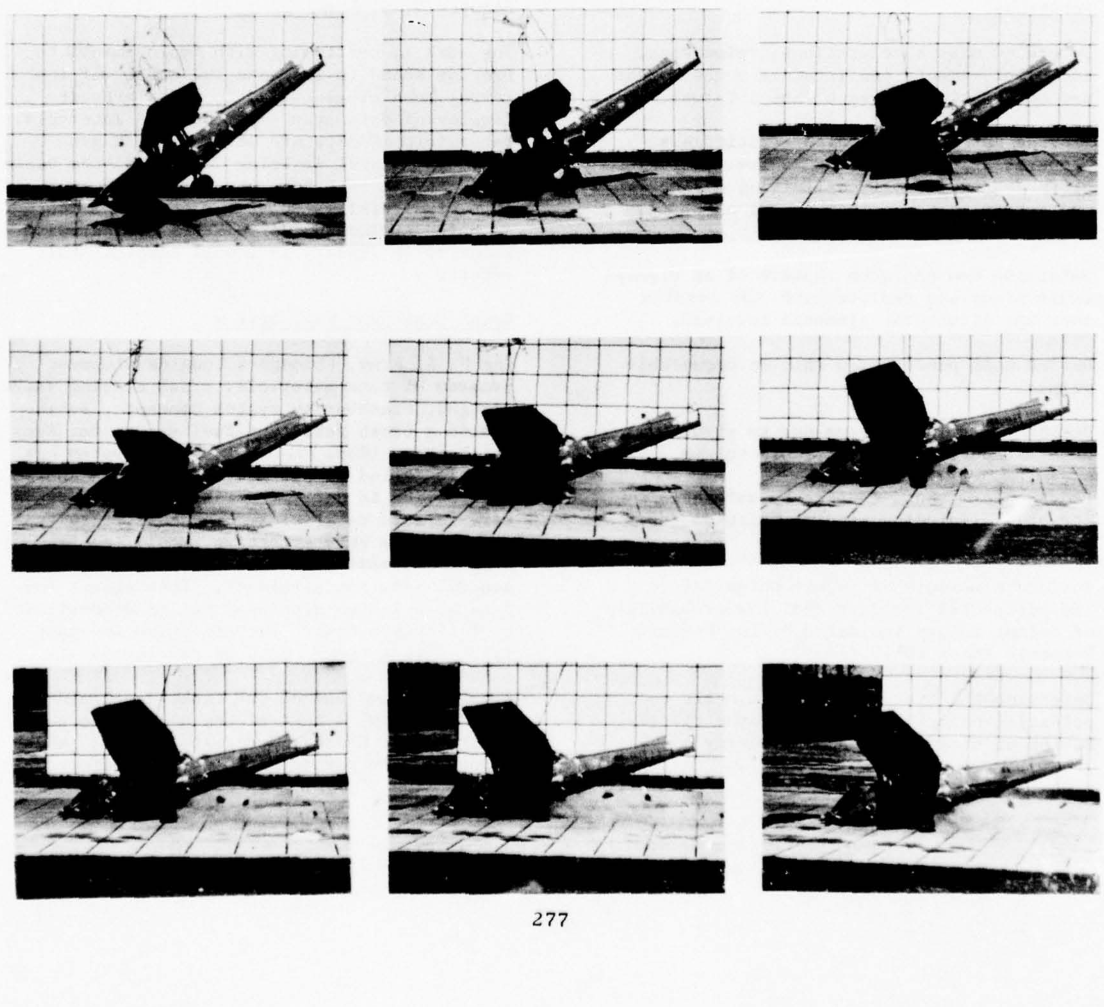


Figure 3 - Sequence Photographs of Full-Scale Crash Test



been developed that has a measure of verification which could treat a complete structure. This model was Program KRASH, initiated by the U. S. Army-Eustis Directorate (Ref. 4, 5, and 6).

Competitive bidding procedures were used and a contract was awarded to Lockheed-California Company with Cessna Aircraft Company to continue the development of Program KRASH, to make it applicable to general aviation, to simplify its use and to verify the program with full-scale crash tests of a typical general aviation airplane.

Program KRASH is a computer mathematical simulation program in which the airplane is modelled as a series of interconnected lumped masses (Figure 2). Each mass is allowed six degrees of freedom, three translations and three rotations. The masses are connected internally by no-mass nonlinear beam elements. Each mass is allowed up to three external springs which radiate outward from the mass and contact the ground, providing external crash forces. Program KRASH has the capability to:

1. Define the response of six degrees of freedom (DOF) at each representative location, including three translations and three rotations.

2. Determine mass accelerations, velocities, and displacements and internal member loads and deformations at each time interval.

3. Provide for general nonlinear stiffness properties in the plastic regime, including different types of load-limiting devices, and determine the amount of permanent deformation.

4. Determine how and when rupture of an element takes place and redistribute the loading over the structural elements involved.

5. Define mass penetration into an occupiable volume.

6. Define the volume change due to structural deformations of the occupiable volume.

7. Provide for ground contact by external structure including sliding friction and a non-rigid ground surface.

8. Include a measure of injury potential to the occupants; for instance, the probability of spinal injury indicated by the Dynamic Response Index (DRI).

9. Determine the distribution of kinetic and potential energy by mass item, the distribution of strain and damping energy by element, and the crushing and sliding friction energy associated with each external spring.

10. Determine the vehicle response to an initial condition that includes linear and angular velocity about three axes and any arbitrary vehicle attitude.

11. Provide a measure of the airplane center-of-gravity velocity by means of translational momentum relationships.

12. Analyze an impact into a horizontal ground and/or inclined slope.

13. Analyze a mathematical model containing up to 80 masses and 100 internal beam elements.

Four full-scale crash tests were performed at the NASA-Langley Research Center Impact Dynamics Research Facility, using a single engine high wing airplane (Figure 3) prepared for testing by Cessna. About 50 channels of data were recorded and 20 cameras, internal and external, covered the crash sequence. The comparison of predicted results with analytical results were good. Typical data is shown in Figures 4, 5, 6 and 7.

The work is continuing with improvements to Program KRASH to increase the number of internal beam elements and to add a graphic display of data over selected time intervals. Parametric studies are being made, a programmer's manual is being developed, the basis for criteria is being established and another type of aircraft structure from NASA's tests is being evaluated. A workshop/seminar with industry in January 1979 will complete this effort.

Crash Resistant Fuel System

The U. S. Army, through a long development program of tank materials, crash closing valve designs, crashworthy system concepts, established a crash resistant fuel system for Army helicopters (Ref. 7). This system has been installed in all Army helicopters and in the service, to date, there have been no crash fire related fatalities. These military type tanks, while very effective, would impose weight and cost penalties if applied to general aviation airplanes. This effort for general aviation airplanes was to demonstrate by full-scale tests that effective low-cost light-weight tanks could be developed.

Figure 8 shows one of the tanks developed and Figure 9 shows a test of the tanks into poles and rocks at NAFEC. Goodyear, UniRoyal and Aeroquip have participated in this effort.

Figure 4 - Comparison of Predicted Failures and Test Failures

Location	Test 1 Analysis	Test 1 Test
Seat Leg Failures		
Pilot Forward	Yes[(b)]	Yes
Pilot Rear	Yes	Yes
Copilot Forward	Yes[(b)]	Yes[(a)]
Copilot Rear	Yes	Yes
Tailcone Yield or Failure	Yes	Yes
Noise Gear Failures		
Lower Support	Yes	Yes
Upper Support	Yes	Yes
Main Landing Gear Failures		
Gear	No	No
Support Structure	Yes	Yes
Wing Spar Failures		
Left Wing	No	No
Right Wing	Yes	No
Wing Column Strut Failures		
Left Wing	Yes	No
Right Wing	Yes	No
Engine Mounts Buckle	Yes	Yes

(a) Pulls loose from track.
(b) Based on stress ratio $\geq$ 1.25 for either inboard or outboard leg.

Figure 5 - Comparison of Predicted and Test Impact Sequence

Sequence	Time - Seconds (a) Predicted	Time - Seconds (a) Test
. Noise Gear Impact	0	0
. Noise Gear Support Structure Failure	.08-.011(b)	.012
. Engine Lower Structure Impact	.051	.034
. Engine Spinner Impact	.570	.046
. Lower Firewall (left side) Impact	.054	.050
. Right Main Landing Gear (M.L.G.) Tire Impact	.066	.060
. Right Main Landing Gear Bulkhead Failure	.095	.082
. Left Main Gear Tire Impact	.075	.080
. Forward Seat Leg Failure (Pilot)	.086-.090	.095
. Maximum Left MLG Tire Deflection	.090	.100
. Tailcone Yielding	.102	.108

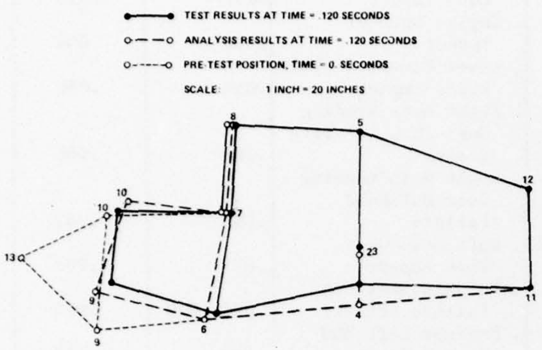
(a) After initial impact
(b) Lower support followed by upper support attachment failure

Figure 6 - Comparison of Analysis and Test Structure Responses

Location	Direction	Analysis G-Peak	Analysis Time(a)	Test G-Peak	Test Time(a)	Percent Difference (b)	Time Difference (c)
Engine	Up	52.8	0.066	40.0	0.050	-32.0	-0.016
	Aft	66.0	0.078	52.0	0.058	-27.0	-0.020
Forward Fuselage Floor, F.S. 27	Up	52.0	0.087	50.0	0.095	-4.0	0.008
	Aft	47.0	0.090	50.0(d)	0.095	6.0	0.005
Landing Gear Floor, F.S. 60	Up	34.8	0.108	36.0	0.110	3.3	0.002
	Aft	33.5	0.066	27.5	0.094	-21.8	0.028
	Aft	30.0	0.084	30.0	0.110	0.0	0.026
Aft Fuselage Floor, F. S. 90-108	Up	21.8	0.108	28.0	0.113	22.4	0.005
		47.1	0.114	28.0	0.113	-68.2	-0.001
	Aft	37.3	0.067	36.0	0.038	-3.6	-0.025
		35.6	0.108	35.0	0.113	-1.7	0.005
Wing B.L. 100.0	Up	33.3-35.7	0.111-0.120	33.0	0.098	-1.0to-8.2	-0.013 to-0.022
	Aft	39.4	0.075	27.0(e)	0.090	-45.9	.015

(a) Time in seconds after impact.
(b) Percent difference $= \frac{\text{Test - Analysis}}{\text{Test}} \times 100$
(c) Time difference = Test Time - Analysis Time
(d) Disregards sharp pulse.
(e) Polarity may be reversed.

Figure 7 - Comparison of Analysis and Test Cabin Deformations



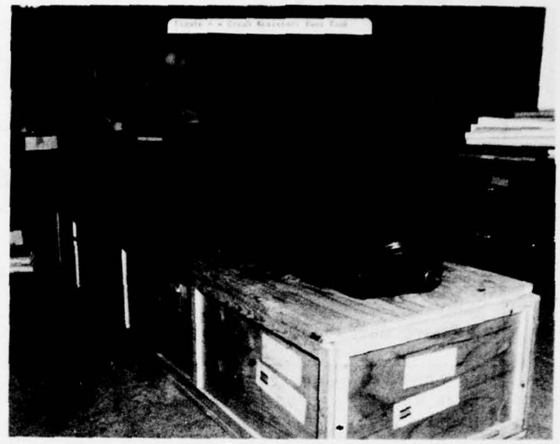


Figure 8 - Crash Resistant Fuel Tank

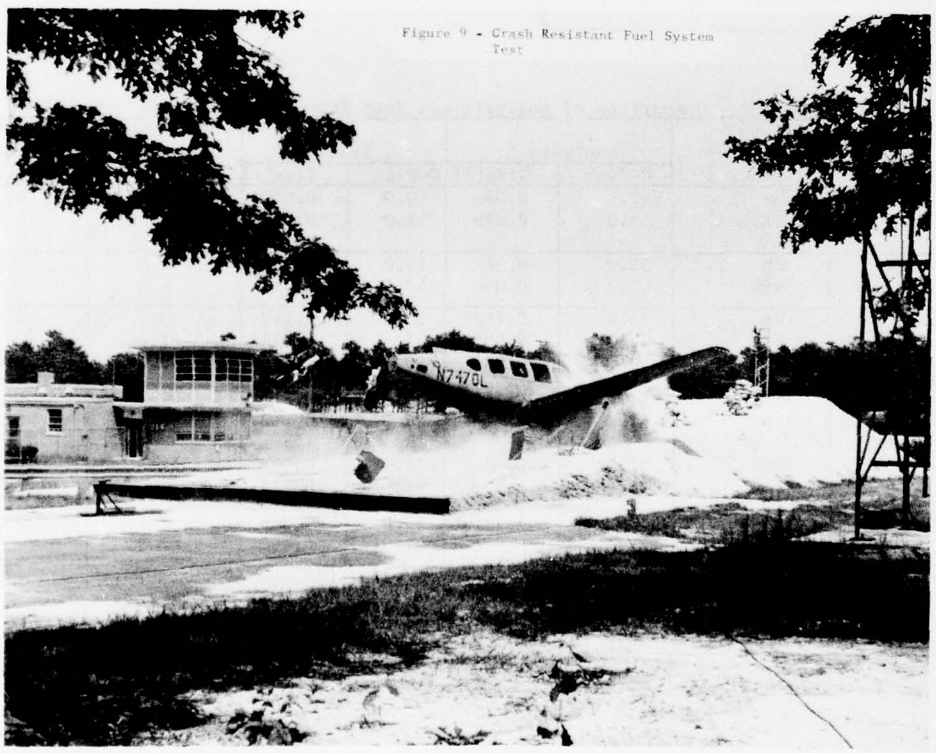


Figure 9 - Crash Resistant Fuel System Test

Four tests at about 63 mph have been conducted using the original bladder cell, one, two and three-ply $12\frac{1}{2}$ ounce per square foot per ply material, and eight ounce and five and one half ounce single ply material. There were no failures of the tank material and no fuel spillage for the $12\frac{1}{2}$ ounce one, two , and three-ply tanks. The original tank and the five and a half ounce single-ply tank ruptured in the test releasing a fuel spray. The eight ounce single-ply tank ruptured and allowed fuel to run from the tank. These tank developments and tests indicate that a volume penalty of less than one gallon from the original 59-gallon tank can be achieved with a weight penalty of nine pounds over the original 10-pound tank.

Transport and Helicopters

The results of the general aviation aircraft crashworthiness studies show good promise for future application to design. Cessna, Bell Helicopters, Sikorsky and NASA are putting Program KRASH and SOMLA on their computers. The next step are studies applicable to the transport airplane and helicopters.

Crashworthiness is being included in the Helicopter Safety Program Plan. In this effort, the general aviation seat model Program SOMLA will be modified to represent the accident environment, improved energy absorption and to add features which will make it more useful for military purposes. The airframe structural response model Program KRASH will need little modification and will be used to predict results of crash tests of helicopters modified with crashworthy structure, seats and fuel system. Fuel system development will be a substantial part of the effort to develop crash criteria and systems for civil usage. NASA-Langley Research Center will participate in the crash tests and CAMI and the U. S. Army in the seat program.

Transport aircraft by virtue of their size present vastly different problems than the general aviation airplane or helicopter. In this effort, the seat model Program SOMLA will be modified to handle double and triple seats and crash impact criteria for input will be developed. Crashworthy fuselage fuel systems and design criteria will be developed. Consideration for crashworthy fuel tanks will be given to other volumes such as wing-fuselage fairing tanks and wing-leading edge tanks.

For transport structural response, Program KRASH probably will not be applicable due to the size of structure to be represented and new techniques will have to be developed.

A joint program to improve transport crashworthiness is being developed with NASA.

SUMMARY

1. A user oriented three-dimensional computer mathematical model of general aviation airplane seat, occupant and restraint system has been developed - Program SOMLA.

2. Full-scale dynamic tests to verify and improve Program SOMLA are being conducted at CAMI.

3. A user oriented computer mathematical model of general aviation airplane basic structure and crash impact environment has been developed - Program KRASH.

4. Full-scale dynamic crash tests to verify and improve Program KRASH have been conducted and the correlation with predicted results is good.

5. General aviation crash resistant fuel system technology has been demonstrated with full-scale crash tests.

6. Future work will include both transport airplanes and helicopters.

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THE FAA SECURITY R&D PROGRAM - 1978

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BIOGRAPHY

Gerald Carp is the Chief of the Aviation Security Branch responsible for research and development in aviation security. He received his BEE from CCNY and his MEE from the Polytechnic Institute of Brooklyn. Before joining the FAA in 1977, he spent two years teaching electrical engineering at City College, ten years as Chief of the Radiation Effects Branch at ECOM doing research on nuclear weapons effects, eight years with the General Electric Company designing major systems for detection of nuclear detonation, two years with the General Learning Corporation as Director of Advanced Development responsible for applying modern technology to the educational process, six years with the MITRE Corporation where he was responsible for the design and development of unattended ground sensors for military applications and two years with the Drug Enforcement Administration as Chief of the Advanced Technology Branch.

ABSTRACT

This paper reviews the current state-of-the-art of bomb detection, identification and neutralization techniques applicable to airport and aircraft safety. Primary emphasis is placed upon the efforts supported by the Federal Aviation Administration (FAA) and the requirement that these systems be useable in the commercial aviation environment. Among the FAA programs described are the development of detection systems based upon thermal neutron activation, automated X-ray image recognition, nuclear magnetic resonance, and macrosmatic animals. The specific approaches and performance of these systems are given along with a description of planned R&D programs designed to develop improved techniques and systems for aviation security.

A new concept, deactivation "tagging" of explosives by the addition of special materials during manufacture, which seeks to neutralize or sterilize bombs during routine screening operations, is described and candidate means of accomplishing deactivation are presented.

INTRODUCTION

The Federal Aviation Administration (FAA) is confronted with a number of security problems which present challenges and opportunities to the technical and industrial community. All airline travelers are aware of the security screening, metal detectors and imaging X-ray systems used for anti-hijacking and sabotage prevention. This program has been successful - in 1977 none of the five hijackings of the United States (U.S.) air carriers occurred because of weapons penetrating the screening system - nor were there any bombings.

The most challenging current problem, the one receiving a great deal of the FAA attention, is the detection of bombs in luggage and air cargo. Current approaches to bomb detection are based on the measurement of natural unique vapors or bulk properties of explosives and/or associated components. Alternatively detection may be approached by the use of taggants, special materials added during the manufacturing processes to aid in the detection of explosives. Also under consideration is deactivation "tagging", the addition of special materials during manufacture which will permit neutralization or sterilization of bombs during routine screening operations.

Although there are many U.S. requirements for bomb detection systems, this paper will emphasize the FAA requirements and programs. The FAA program emphasizes the detection of untagged explosives; other federal agencies programs emphasize tagging-based systems. Following is a description of the required screening system performance characteristics, current R&D programs for bomb detection systems and new approaches under consideration.

FAA Bomb Detection System Requirements

To place the FAA program into perspective, I will first review the environment in which an explosive screening system must technically and economically operate.

First some U.S. statistics for 1977:

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	U.S.	FOREIGN	TOTAL
carriers	36	72	108
airports	450	168*	618
aircraft	2,500	-	2,500
flights per day	13,600	500	14,100
passengers per day	650,000	35,000	685,000
passenger checked bags per day (approx.)	1,000,000	50,000	1,050,000
carry-on items per day	880,000	50,000	930,000
air cargo	5.1 million tons		

* Served by U.S. carrier and/or final departure point for foreign carrier flights to the U.S.

The foreign column represents service to and from the U.S. by foreign carriers. Further, the security system must not only be capable of handling the current passenger enplanements but also the projected growth to some 300 million per year in 1982 and 400 million per year by 1989. Although there are 900 air carrier airports, about 45 carry well over 80 percent of the traffic. Thus, the security screening systems being developed are primarily aimed at these high volume airports such as O'Hare, Chicago, John F. Kennedy, New York and Los Angeles International, California. The smaller feeder airports can employ simpler (less expensive) hand search techniques.

The constraints under which the system must operate are:

o The flow of people and baggage should not be inhibited in a manner which could create unwarranted delays.

o The system must be reliable, easily maintained and operable by relatively untrained personnel.

o The system should not present a safety hazard or otherwise be harmful to the environment.

o The system should not damage the contents of luggage in any way, nor present an invasion of privacy.

o The system/procedures should not present an unwarranted financial burden to the airlines, airport owners or passengers.

The critical parameters of a screening system are:

Throughput - The average rate at which checked luggage can be screened; studies indicate a minimum of 10 bags per minute is required.

Detection Rate - While 100 percent is desirable, a somewhat lower rate would still create an unacceptable risk to a would be bomber. The FAA currently feels that a 90 percent detection rate will provide a credible deterrent.

False Alarm Rate - Given that adequate detection and inspection rates are achieved, system operating cost is highly sensitive to false alarm rate. In any system, all alarms must be treated as real alarms until proved otherwise. No bomb detection system can treat an alarm casually. Yet evoking a full explosive ordinance disposal (EOD) response to an alarm is costly and time consuming. An alarm rate as low as one percent would, in the U.S., involve some five million bags per year, or approximately six bags per fully loaded 747 aircraft. With the unlimited variety of contents "normal" to passenger baggage (we have encountered some 30 pounds of three foot long screwdrivers in one suitcase, several large salamies and cheese in another and candelabrum in still another) maintaining the necessary detection and throughput rates with acceptable false alarm rates is the most challenging problem facing bomb detection system designers.

CURRENT R&D PROGRAMS

Current FAA bomb detection R&D programs are directed at the detection of normal or natural explosives rather than tagged explosives. Tagging which involves the addition of some material with unique properties to the explosive during manufacture is being actively pursued by the Bureau of Alcohol, Tobacco and Firearms (ATF)[1]. Enabling legislation (S.2013) requiring the addition of taggants into all legal nonmilitary explosives manufactured or imported into the U.S. is being considered by the 95th Congress. The FAA emphasis on untagged detection avoids duplication of effort with ATF and addresses explosive security for U.S. airlines, where, particularly during overseas operations, untagged explosives may be a threat.

Vapor Detection Programs

Vapor detection programs are based upon the presence of one or more vapors unique to each explosive. The existence of such vapors has been demonstrated by the performance of specially trained dogs which have detected explosives at rates on the order of 90 percent. Unfortunately, dogs require handlers and the team, while effective, is too costly, for routine screening. Electronic explosive vapor detectors such as the electron capture devices currently on the market can readily detect nitro based dynamite but do not respond to C-4 and some other explosives. Unfortunately, most electron capture devices also respond to many other substances such as shaving lotion, shoe polish, etc., which are commonly found in luggage and airport environments. Moreover, their typical sensitivity, of the order of 1 part in 10^9 is inadequate for effective operational use[2]. In general, none of the currently available commercial explosive vapor sensors meet

operational airport use requirements.

Explosive Vapor Characterization

IIT Research Institute, Chicago, Illinois

The objectives of this program include identification and measurements of partial vapor pressures of substances and their degradation products that might be used to characterize explosives of interest and ambient air in and about airports. These will allow formulating models relating vapor concentrations of explosives concealed in luggage, aircraft, lockers, etc., to concentrations which may be available for detection under practical operational conditions.

Preliminary analysis of several samples of vapors from different explosives have shown up to 400 chromatographic peaks, some of which appear to be unique. Although many of these peaks have been identified, at the time of preparation of this paper, quantitative measures of their vapor pressure have not been completed. This program is expected to provide a quantitative and qualitative specification of vapors characteristic of explosives of interest and will be used as the basis for a program to develop new explosive vapor detection systems. Scheduled completion date is August 1979.

Study to Determine the Validity of Biological Bomb Detection

VA Hosptial Medical Research Wing, Philadelphia, PA.

Dr. G. B. Biederman has trained a number of gerbils (meriones unquiculatus) to detect a variety of explosive and other vapors at dilutions substantially greater than has been achieved with physical devices.[3] While this work represents a greater level of performance than had here-to-fore been reported, a number of operationally significant questions remained unanswered. Early in 1978, the FAA initiated a two year program with Dr. D. Moulton of the Veterans Administration to determine the sustained performance of gerbils and domestic rats in olfactory discrimination, the best training method to develop the animals for placement in an explosive detection system, and the effective repertoire of odors that these animals can be trained to detect. Among the questions to be answered by this study are:

--How do composition variations of the same explosive manufactured in different batches or by different manufacturers effect performance?

--What are the effects of masking odors on animal performance?

--What is the animals effective working period?

--Does random variation of the concentration of sample vapors effect performance?

--What is the optimum conditioning for training animals?

--What is the temporal distribution of errors - false positive and false negatives?

--What is the correlation of errors among multiple animals exposed to the same sample stream?

At the same time that the FAA is pursuing a scientific extension and validation by Dr. Biederman's work, other organizations will test systems supplied by Dr. Biederman in a working/operational environment.[4] The scheduled completion date of this program is March 1980.

Decompression Screening System

Transportation Systems Center, Cambridge, Mass.

A problem associated with the use of vapor for measurement is acquiring the maximum available concentration of explosive vapor for measurement. In a nonautomated environment, the sampling probe is placed near seams and keyholes in a suitcase. In automated environments, one means for sampling has been to pass the luggage through an air curtain. The FAA has developed an automated technique for passing luggage into a sealed chamber, minimizing the enclosed volume and collecting a vapor sample from inside the luggage by evacuating the chamber. An experimental model, Figure 1, was delivered in early 1978 and is now entering operational testing.

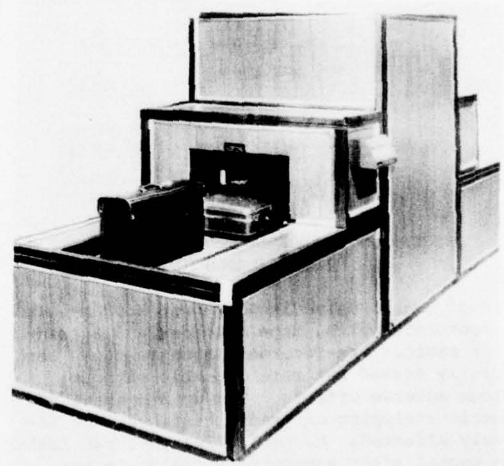

FIGURE 1. EXPERIMENTAL DECOMPRESSION SCREENING SYSTEM

Preliminary results indicate the vapor samples extracted from the bags were diluted to only 40 percent and at a throughput of eight bags per minute.[5] This represents an improvement on the order of 10^3 in vapor concentration compared to air curtain sampling and is applicable to any type of vapor detector.

BULK DETECTION SYSTEMS

The FAA is currently developing three different types of bulk detection systems. Nuclear Magnetic Resonance and Thermal Neutron Activation Systems based upon the chemical or atomic properties of the explosives, and an X-ray Absorption system based upon the physical size and X-ray characteristics of the explosives. The latter system is in essence a bomb detector rather than an explosive detector.

Nuclear Magnetic Resonance (NMR)

Southwest Research Institute, San Antonio, Texas

Following a feasibility study in 1975, the FAA funded the development of an operational prototype explosive detector based upon the hydrogen NMR response of explosives.[6] Figure 2 shows a block diagram of the feasibility model NMR system. The feasibility study demonstrated the capability to detect quantities of less than one pound of explosive in a sample volume of 14 in. X 23 in. X 15 in. Means to discriminate against the response from nonexplosive items were developed and incorporated into the apparatus.

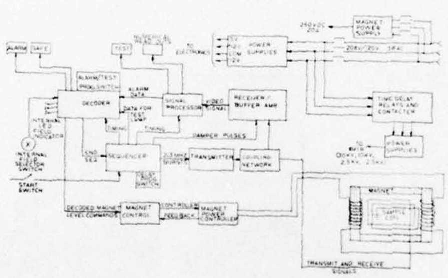

FIGURE 2. BLOCK DIAGRAM OF NMR LUGGAGE INSPECTION SYSTEM

Tests of nonexplosive items showed no damage to an electronic watch, tape recorder and a transistor radio. Pre-recorded magnetic tapes were partially erased but were reusable without obvious adverse effects. The data content of magnetic stripping on credit cards was not adversely effected. Mechanical watches ran faster than normal after exposure to fields in the apparatus but were restored to normal operation by demagnetization. Tests with electrical blasting caps connected in normal firing circuits did not result in any detonations. Tests with and without simulated explosives gave correct indications greater than 83 percent of the time. The errors were associated with inhomogeneities in the polarizing magnetic field, a problem being addressed in the current development program.

The current program is scheduled to provide a prototype unit for operational airport tests by September 1978.

Thermal Neutron Activation

Westinghouse Research Center, Pittsburgh, PA.

The thermal neutron activation explosive detector is based upon the thermal neutron reaction ^{14}N (n,) ^{15}N with nitrogen, an element common to all explosives. In this reaction, the ^{14}N nucleus captures a thermal neutron to form excited ^{15}N which promptly emits a 10.8 MEV gamma photon in approximately 15 percent of the reactions.

To avoid false alarms due to the presence of nonexplosive nitrogeneous materials such as wool, orlon, silk and leather, the detector system senses the density as well as the quantity of nitrogen. Nitrogen density is much greater for explosives than normal baggage contents. Figure 3 shows a typical nitrogen density profile for a bundle of dynamite in a large suitcase. Background was suppressed by setting the threshold at 211.

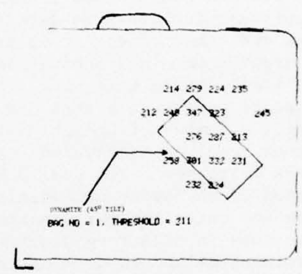

FIGURE 3. NITROGEN DENSITY PROFILE OF DYNAMITE IN A LARGE SUITCASE

The results from a feasibility study showed that even with the low resolution imaging system employed in the experimental detector, bombs large enough to damage an aircraft could be easily detected and that there was no difficulty in discriminating against shoes and large numbers of orlon sweaters.[7]

The current program will develop an operational prototype neutron activation explosive detector. The first phase is the fabrication of a transportable experimental system which will be used

at several airports to acquire data on typical passenger luggage. The use of actual luggage cannot be overemphasized. Experience has shown that simulation of the broad variety of luggage and contents encountered in commercial aviation is impractical. Realistic system evaluations require the use of statistically significant quantities of "real world" luggage.

The experimental system is scheduled for airport test May 1979.

X-ray Absorption

Westinghouse Research Center, Pittsburgh, PA.

The X-ray absorption bomb screening system for checked baggage is the first system to have successfully passed airport operational testing.

In operation, a relatively low resolution (2 cm X 2 cm) digitized X-ray transmission image is computer processed to automatically sound an alarm when the programmed criteria for one of several typical bomb configurations are encountered. In operation, a ^{133}Ba radioisotope is collimated into a fan beam which illuminates a vertical line of 48 NaI(Tl)/photo-multiplier scintillation detectors. The bag is carried past the line of detectors on a moving belt. Under computer control, the analog outputs from the detectors are scanned, digitized and passed to a LSI-11 mini computer for processing. Figure 4 shows the basic structure with covers and luggage belt removed. On the right side are the 48 photomultiplier tube assemblies in the lead collimating shield. On the left is the lead pig containing the ^{133}Ba source together with the collimating slits which defines the fan beam of radiation. Two different algorithms have been evaluated. The first, developed by the Westinghouse Research Center identifies all pixels where a preselected absorption threshold is exceeded and applies a set of pixel connectivity rules to identify images characteristic of bombs.

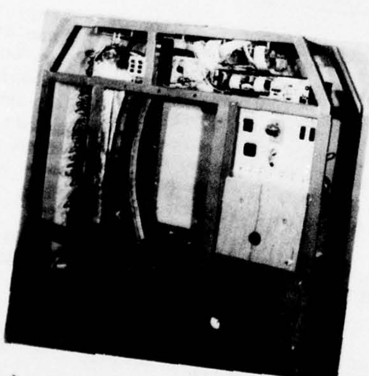

FIGURE 4. X-RAY ABSORPTION UNIT, COVER AND BELTS REMOVED

The criteria for bomb detection are based upon the analysis of data from more than 8000 randomly selected bags at Newark International and Washington National Airports. Simulated bombs were added to approximately 25 percent of these bags.

Typical performance against this data is 85 percent detection with less than 15 percent false alarms while screening bags at the rate of one per second. Performance is quite sensitive to absorption threshold selection and may be varied to maximize detection or minimize false alarms.

A second processing algorithm being developed by the MITRE Corporation using the same data base takes a more global view of the data. To date, using three features, contrast, O (a measure of goodness to fit), and the minimum transmissivity over a scanning window better than 97 percent detection was achieved at less than 5 percent false alarms. Figure 5 illustrates the results achieved for dynamite and C-4 based bombs using these criteria. The dashed curves are the results achieved with the Westinghouse algorithm. Both are based upon the same data. Table 1 summarizes the basis of the MITRE algorithm results. Here too the criteria can be adjusted to emphasize detection at the expense of false alarms. A major difference between the two algorithms is that the MITRE algorithm does not require preselecting a fixed absorption threshold, a quantity that appears to be sensitive to the airport location. It is anticipated that further performance improvements will be realized as new features are used in the pattern recognition algorithm.

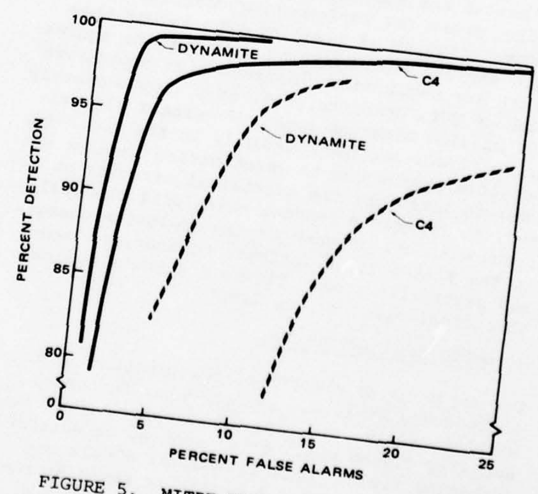

FIGURE 5. MITRE EXPERIMENTAL RESULTS

TABLE 1. BASIS OF MITRE ALGORITHM RESULTS

o DATA BASE - 1344 SUITCASES

(747 CLEAN, 306 DYNAMITE, 291 C-4)

o THREE FEATURES (2 WINDOWS)

o MINIMUM

o Q (A MEASURE OF GOODNESS TO MATCH)

o CONTRAST DIFFERENCE

o TRAINING SET (20 CLEAN, 20 DYNAMITE, 20 C-4)

o RESULTS (EQUAL THRESHOLD)

o 97.3 % DETECTION

o 4.8 % FALSE ALARMS

Deactivation Tagging

Detection and removal has been the classical approach to the bomb problem. More recently, consideration has geen given to an alternative, automatic deactivation or neutralization of the bomb during routine screening. From a system point of view, deactivation is attractive in that it may avoid a major system cost, the personnel required to respond to system alarms, real or false. Studies of typical candidate bomb detection system airport installations suggest that personnel costs account for approximately 90 percent of the cost.

Using the current state-of-the-art, deactivation could be accomplished by the addition of a special "Tag" during manufacture of explosives. Technical and economic considerations of alternative means for implementing deactivation suggest tagging of blasting caps rather than bulk explosives. Blasting caps (or the equivalent) are required to initiate high explosives such as TNT, dynamite, C-4, etc. Approximately 100 million blasting caps, 80 percent electrically fired, are used annually in the U.S. Two possible approaches to deactivation tagging are one; to interrupt the electrical circuit; or two, to release a reagent which will chemically react with one or more of the explosive charges in the firing train (primer, booster, or base) and neutralize them. Figure 6 shows a typical electrical blasting cap (EBC).

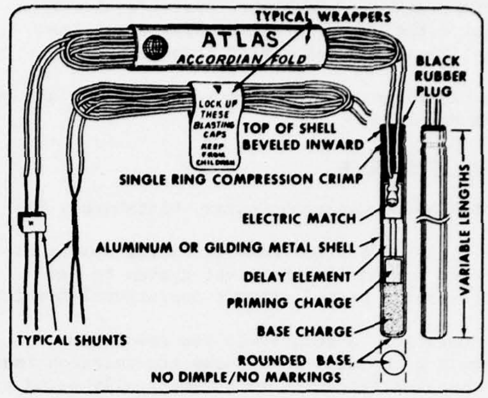

FIGURE 6. ATLAS ELECTRICAL BLASTING CAP

Magnetic Reed Switch Tag

One approach to electrical deactivation is to introduce a miniature switch/relay in series with the firing circuit. This switch would be normally closed until acted upon by an external screening field. Once opened, it should be impossible to reset. A miniature remanent reed switch meets many of the criteria for such a device except resistance to reset. When presented with this problem, R. M. Riley and his colleagues at the Bell Laboratories, Columbus, Ohio, came up with an innovative solution; the addition of a small amount of powered (non-conducting ferrite to a remanent reed switch. Once the switch is opened, the ferrite is attracted into the high magnetic flux region between the contacts precluding resetting the relay. At the present time, there are no sub-miniature remanent reed switches (with or without ferrite powder) in production. One would have to be developed should this approach be pursued.

Frangible Capsule Tag

Conceptually, the incorporation of a reagent in a frangible capsule inside a blasting cap is extremely attractive. It could be used on both electrical and non-electrical blasting caps. The quantity of reagent required would most likely be quite small since typical quantities of explosives in the blasting cap range from approximately 0.2 grams for the priming charge and the booster charge to 0.4 grams for the base charge.

No reasonable approaches for implementing such a deactivation tag have been received. Some thoughts on the problem include:

For activation, use low frequency magnetic fields that can readily penetrate the conducting shell of the blasting cap.

. Form the capsule from pre-stressed glass so that minor additional stress will result in rupture.

. Include a "tell-tail". Some means of indicating that the cap has been deactivated is needed for blasting caps used in legal blasting operations.

Future Activities

While each of the ongoing FAA R&D programs in bomb detection have high probabilities of successful performance in operational scenarios, they are far from panaceas. If used singly, each can be countermeasured. If multiple disparate technologies are used in cascade, countermeasures become extremely difficult but costs and false alarm rates increase. The FAA is continuing its search for most cost-effective solutions to aviation security.

Among the new approaches currently under consideration are dual energy X-rays and computerized tomography. Dual energy X-ray measurements permit measures of photoelectric and compton absorption coefficient, from which the atomic number and electron density of the materials being screened can be estimated. This has promise of extending the capability of X-ray based systems beyond the detection of size and density to material composition and enable direct detection of explosives as well as bomb-shaped packages. Computerized tomography which can provide multiple slice high resolution images if coupled with dual energy measurements could potentially detect bombs/explosives in luggage even if they were in the form of pipe bombs or rolled out plastic explosives. Moreover, it should be able to do so even if shielding is attempted. Obviously, large amounts of shielding could "hide" a bomb, but that in itself would be detected and be cause for alarm. Study contracts to assess the practicality of these approaches will be completed in 1979.

CONCLUSION

The FAA security system is adequate to meet the current threat. Research and development is continuing on more cost-effective security screening systems which will be capable of meeting new and more violent threats to aviation. Worldwide, there is a continuing increase in terrorism coupled with growing alliances and cooperation among international terrorist organizations. Achieving the necessary high level of security in civil aviation is costly, but necessary.

The FAA security program is geared to developing enhanced capabilities which can be quickly deployed when it becomes necessary to do so. While we believe we are addressing all known attractive approaches to solving this difficult problem, the door is always open to new approaches. Any suggestions will receive thorough consideration.

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AIRMAN SAFETY

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BIOGRAPHY

Patrick E. Russell is the airman safety program manager for the Aircraft Safety and Noise Abatement Division, Systems Research and Development Service (ARD). He was educated at the University of Minnesota, Gonzaga University, and the US Naval Post-graduate School, Monterey, California. In his 11 years with the Federal Aviation Administration (FAA), he has managed such diverse projects as Lightning Hazards to Aircraft, Bird Ingestion Hazards to Jet Engines, Anti-Hijacking Techniques, and Transport Aircraft Crash-Fire Hazards. During the last 5 years, he has been involved in civil pilot training and evaluation projects. His three tours in the US Navy Pilot Training Command as primary flight instructor school student, flight instructor, and ground instructor equip him to contribute to civil pilot safety through improved training.

ABSTRACT

Four projects which deal with airman safety are discussed. The pilot skill degradation study identified which skills suffer and to what extent and with what type accidents they may be linked. The next two projects developed flight training syllabi responsive to the stall/spin accident and the 80 percent pilot judgment causal factor accident. The entire civil pilot training curriculum through the flight instructor rating is under study in the final project.

BACKGROUND

In its broadest terms, "airman safety" covers the entire spectrum of aviation safety. Our interests in this paper are limited to the pilot only. We are concerned with his skills, knowledge, training, proficiency, and basic humanness; not with his susceptibility to injury or the aircraft's crashworthiness and cockpit standardization.

The basic objectives, then, of this program have been, and continue to be, to reduce the fatal accident rate by providing insight into the cause behind the cause, by ferreting out the pilot's weakness responsible, and by the development of superior training for civil pilots - students, private, commercial, and instructor.

The form and content of the reported effort are largely dependent upon the technical nature of the request from the customer; i. e., Flight Standards Service, Office of General Aviation (AGA), etc. The customer and ARD program office are partners in the effort from the time of the request to the publishing of the results. All decisions, evaluations, and goals are joint.

PRODUCTS/EXPECTED RESULTS

Elements of the program can be listed in the following order and will be addressed accordingly:

I. Pilot Skill Degradation.
II. Stall Awareness Training.
III. Pilot Judgment Training.
IV. Ground and Flight Training Syllabus Improvements.

I. Pilot Skill Degradation

Background. Quite clearly, one cannot determine posthumously what skills the dead pilot lacked nor to what degree those skills were tarnished. Therefore, as an alternate route, one could mount an investigation of a statistically valid sample of pilots to determine where the weaknesses lie. A comparative analysis of these weaknesses against the causal factors of fatal accidents would confirm or deny a relationship which would identify the existence of, or lack of, a problem. The problem could be addressed by training, regulation, or both. Such an effort was completed under contract to the Department of Aeronautics and Astronautics of the Massachusetts Institute of Technology (reference 8). If skill degradation could be linked to specific quantities of flight time; i. e., total, recent, and in type, the FAA would be provided the data necessary to legislate flight experience/currency requirements.

A final report was produced and distributed in 1974. Data provided by the report essentially confirms the schedule and requirement for the biennial review entered into law in 1974.

Technical Approach. A statistically valid sample of 55 noninstrument rated, single engine private and commercial pilots (commercial pilots were not required to hold instrument ratings at that time) were exposed to two written quizzes on aeronautical knowledge and three flight evaluations testing pilot flying skills. These skills were classified as:

Procedural (retention and recall).
Judgment and Problem Solving.
Motor Coordination.

The subject's performance on each phase of flight was graded numerically from 0 to 5 and adjectively from dangerous to perfect. Those factors which contribute to overall skill are:

1. Recency in Type (hours per week).
2. Logarithm of Total Flight Time.
3. Time since Certification (Years).
4. Logarithm of Flight Time in Type.

The variations in skills of the subject pilots were quantified using a statistical analysis of factors (1 to 4) above.

Summary and References

1. The latent skill of the subjects accounts for 30 percent of the variance in skill.

2. Experience factors account for only about 25 percent of skill variance.

3. The remaining 45 percent of variance in skill can be divided among random variations of individual pilots, interaction effects, and "noise" in the measurement process.

4. Recency of flight experience is the most important experience factor affecting score and, therefore, skill.

5. Skill increases with total time at a rate that is inversely proportional to the total time accumulated.

6. The skill degradation which accompanies the normal aging process can be largely accommodated by recency and total experience.

7. The lowest average grades attained were in those skills associated with stalls and simulated instrument flight. Not coincidentally, these two skills are seldom, if ever, practiced by certificated private and commercial pilots, and the lack of these skills are causal factors in a large percent of fatal general aviation accidents (references 1, 7, 12, and 13).

II. Stall Awareness Training

Background. Stall training has been a part of many flight training syllabi during the history of aviation. Until 1949, it was accompanied by compulsory spin training in US Civil Pilot Training schools by direction of Civil Air Regulations. After 1949, stall training remained compulsory, but spins became optional. In the intervening years, the general aviation stall/spin accident rate has decreased by one-half. However, with the increase in the pilot population, more occurrences and, therefore, more fatalities have resulted.

The National Transportation Safety Board (NTSB), in its Stall/Spin Special Study (reference 13), pointed up this problem and recommended that the FAA take action to arrest the trend. As a result, the Stall Awareness Training study was accomplished. It was expected that such a study could point the way to training techniques and/or regulatory action which could reduce the number of stall/spin accidents and fatalities.

Technical Approach. A comprehensive ground and flight training syllabus involving enhanced stall/spin recognition, avoidance, and recovery was conceived, documented, and administered to three experimental groups of low-time pilots under rigidly controlled conditions. In addition, evaluation examinations for both ground and flight training were conceived and administered to a total of 51 pilots consisting of three experimental groups and one control group. The control group received no experimental instruction. The Number 1 experimental group received the experimental ground school only; Number 2, the ground school plus stall training; and Number 3, ground school, stall training, and spin training. The ground school training involved lectures, discussion, and a movie; i. e., FAA, "Stalling for Safety." Lectures covered the history and regulatory aspects of stall/spin training, a description of the elements of current pilot training, accident statistics, aerodynamics (including forces and moments in a spin), and descriptions of stalls and spins in scenario form. The experimental flight training made use of the scenario form in addressing short field takeoff; engine failure on takeoff or initial climb; cross controlled turns to final approach; skidding and slipping turns to final approach; overtaking slower traffic (primarily in the pattern); power loss on final approach; recovery from high sink rate; go-around with full nose-up trim or with premature flap retraction; left turning tendency on a go-around in a right cross-wind; flight at minimum control airspeed/high angle of attack; and incipient spins, spin avoidance, and spin training.

Evaluation flights were administered before and after the training increments. They were highly structured and placed a premium on the subject's ability to maintain control of the aircraft within the speed range of the stall warning system. A lower grade resulted when the subject allowed the vehicle to stall, stall/spin, or attain a speed above stall warning.

Concomitantly, the subject was exposed to such distraction scenarios as navigating, using a map, communicating with the Flight Service Station for weather information, locating ground reference points, and retrieving items about the cockpit placed there by the evaluator.

Data was gathered by a video camera and a tape recorder. The camera recorded all pertinent instrument readings, and the tape recorder provided means for a running commentary by the evaluator regarding the subject's performance, apparent thinking processes, and his reaction times. All aspects of the flight were graded and comparative analyses accomplished.

Summary

1. All four groups improved as indicated by a comparative analysis between evaluation flight one and flight two.

2. All subjective flight evaluation grades were positively correlated, improved, and were definitely affected by the flight training.

3. The group receiving the spin training attained the highest score.

4. The group receiving ground training only attained the greatest improvement.

5. Additional flight training on stall awareness and/or intentional spin training has a positive influence toward reducing inadvertent stalls and spins.

III. Pilot Judgment Training and Evaluation

Background. In all pilot training curriculums, space is provided on grading sheets for instructors to assess judgment qualities of students. In the check form used by the FAA in evaluating its own pilots, three separate blocks are provided for evaluating judgment. Yet, nowhere is the term explained, nor is there even a modicum of agreement among pilots (and this includes instructors) what judgment is, how it is attained, and how it is evaluated.

If the student pilot is capable of passing his private pilot certification check ride after 20 hours or 30 hours, why must he attain 35 or 40 to be eligible for the designation? Ostensibly, the additional hours of experience provides the judgmental qualities necessary to justify his exercising the privileges of the pilot certificate. Therefore, judgment has been equated with experience but with no specific evidence to support the equation.

For various professional reasons, the FAA means to solve the equation by:

1. Defining judgment;
2. Determining how it is now being evaluated;
3. Determining whether and how it can be taught;
4. Determining how it can be objectively and accurately evaluated.

Hovering above these rather crisp requirements is the very real assessment that a trainer (or simulator) having undefined characteristics could be used to impart and evaluate judgment. Work sponsored by the FAA in the early 1970's determined that a limited number of skills and maneuvers could be taught in simulators, exclusively or in concert with the training aircraft (references 2, 3, 4, 5, and 6). However, changes to Part 61 in 1974 essentially moved the emphasis in pilot training from the skill and maneuver orientation to the operational requirements orientation.

This philosophy essentially altered the approach to the judgment problem by broadening the scope to include the entire psychological and philosophical disciplines. Therefore, a pilot judgment study was begun in 1976 to seek answers to the four questions posed above.

Products/Expected Results. Phase I effort of this project was contracted to the Institute of Aviation, University of Illinois, and a final report was delivered in April 1978 (reference 11). The direction charted by this effort leads to the establishment of a pilot judgment increment to an established flight and ground training syllabus and a training program to equip flight and ground instructors to administer that judgment training increment.

Technical Approach. The methods used in this initial investigation included literature review, a survey of pilot and flight instructor opinions, and interviews with psychologists and educators. This regimen could only be classified as technical in that a structured, step-by-step process of scientific inquiry was followed. There were no experiments, no data gathered, and no analysis in the technical meaning of the term.

Summary and References. Results of the investigation indicate that pilot judgment can be defined as:

1. "The ability to search for, and establish the true relevance of, all available information regarding a situation to specify alternative courses of action and to determine expected outcomes from each alternative."

2. "The motivation to choose and authoritatively execute a suitable course of action within the time frame permitted by the situation; where: (1) "suitable" is an alternative consistent with societal norms; (2) "action" includes no action, some action, or action to seek more information.

Pilot judgment is not now, in any structured manner, being evaluated in civil flight training, but evidence supports the conclusion that such evaluation is feasible.

Training pilots to demonstrate good judgment is feasible and a method for doing so has been broadly outlined."

3. Within the civil pilot training community surveyed in this study, it was determined that no effective method for evaluating judgment is being accomplished. The reason given primarily is a lack of a clear definition.

Within the US Military Flight Training Commands, judgment evaluation is accomplished before flight training is begun as a screening measure. Psychological battery tests are employed for this purpose.

The Moody Bible Institute, which trains prospective jungle pilots, uses a similar screening technique and, in fact, retains only 50 percent of its applicants after this process is complete. Therefore, one can state that judgment can and is being evaluated in authoritarian environments, but that, as of this time, it is not being evaluated in a structured and repeatable form.

4. The question as to whether judgment can be taught to student (or advanced) pilots appears to be answered by the literature. Some evidence exists that human behavior can and is being altered. That being the case, such techniques are suggested as lending themselves to our purpose. An outline is provided which charts the course for judgment training employing the various techniques suggested by the literature.

5. Several techniques for evaluating judgment are suggested on an experimental basis since no structured method is extant. It would appear that the psychological battery tests administered prior to start of training could be used as guidelines for points of emphasis downstream in the teaching cycle. This technique must not, in civil pilot training, be mistaken for a "screening" test. Such intent would destroy the program considering the privacy rights of a free society.

Techniques employed in medical training using simulated clinical problems and role playing by medical doctor candidates may have real application to ground training. The use of NTSB accident reports as scenarios for developing judgmental criteria against which the student's performance can be compared bears some promise.

This report provides a solid base for Phase II, the actual development of a judgment training and evaluation syllabus, for both students and instructors.

IV. Pilot Training Improvements

Background. Civil pilot training, in a large segment of the US flight training community, has remained essentially unchanged over the years; however, with rapid changes occurring in the aeronautical environment, there is a reason to believe that improvements in training methodology, techniques, and devices are imperative.

The purpose of this study was to improve civil flight training by evaluating innovative techniques and training devices in an experimental environment. Such effort specifically results from recommendations by the NTSB((reference 13) and by a request from AGA.

Products/Expected Results. Phase I of this three-phase multiyear program is complete, and a report has been delivered (reference 11). The product of the three-phase effort is to be in the form of recommendations for revised training methods and syllabi.

Technical Approach. The following tasks constitute the approach taken towards the accomplishment of Phase I:

1. Review flight training (civil, military, and foreign) programs and syllabi to determine what elements of existing training programs could be used advantageously. Include education techniques throughout the academic, training, and scientific communities.

2. Estimate future general aviation aircraft inventory and expected total traffic.

3. Investigate general aviation aircraft cockpit sophistication and the air traffic control environment of the near future (10 to 12 years).

4. Develop a pattern of pilot capabilities required to function in the future environment.

5. Outline elements of an evaluation examination for assessing the capabilities of the pilots trained under an experimental training program.

From the information developed under Phase I, Phase II will develop an experimental training program to evaluate innovations and training devices for development of pilots capable of functioning in a simulated future environment. A complete test plan will be developed to expose participating control group and experimental group pilots to the training program. Phase III will execute the training program and test plan established under Phase II. By comparative analysis of the control group and experimental group performance, advantages, if any, accruing through the use of the experimental syllabus will be determined.

Phase I effort involved survey trips to training sites, a literature search, an evaluation of innovative training programs, a review of FAA estimates of the future air traffic environment, and a review of general aviation cockpit sophistication estimates from various sources. A litany of knowledge, judgmental elements, and skills required of future pilots was developed in response to Task 4. An evaluation/examination

designed to test the student's grasp of the course elements was developed in response to Task 5. In addition, a sample syllabus format was produced which stresses the "mission oriented" training philosophy and the "total integration of ground school and flight school"; that is, each flight follows its exact predecessor ground school class or lecture.

Summary. Completion of this first phase of the overall effort reveals that few really innovative methods exist for training pilots, civil or military. Those methods described represent a spectrum of flight and ground training techniques which are well-known to the flight training community. Their application is dependent upon a number of variables, not the least of which are economic.

Some of the observations, issues, and conclusions, however, are worthy of further thought and perhaps evaluation:

> Systematic and deliberate pilot judgment training through situational scenarios is recognized as a valuable adjunct to pilot training as indicated in the University of Illinois report (reference 10) and Article III above.
>
> The development of mini-courses to be offered as electives beyond the scope of the basic course appears useful.
>
> The development of video-taped lectures by recognized authorities and outstanding instructors as rental or library type loan-out aids or for future use in home TV receivers has great merit.
>
> The use of home TV game type systems for pilot training is truly innovative and possibly not too remote for serious consideration.

The future of this project is presently being considered by the FAA with the possibility that an in-house follow-on to Phase I in which specific techniques would be evaluated individually is a more practical way of developing a firm base for the overall effort than proceeding into a complete Phase II syllabus construction at this time.

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CIVIL APPLICATIONS OF NAVSTAR/GPS

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BIOGRAPHY

Arthur A. Simolunas is the program manager for navigation on the staff of the Director, Systems Research and Development Service (SRDS). He received his B.S. in Electronic Engineering in 1956 from Union College, Schenectady, New York. He initially spent six years with the Link Division of Singer Corporation in Binghamton, New York, before joining the Federal Aviation Administration (FAA) in 1962, at the National Aviation Facilities Experimental Center (NAFEC). His efforts centered on the automation of surveillance radar, the development of cockpit voice recorders, and the field test and evaluation of ARTS I and SPAN ATC systems, the forerunner of the present ARTS III and NAS Stage A Systems. In 1967, he transferred to Washington Headquarters, SRDS, where he participated in the ARTS III design procurement and served as the COTR on the NAS IBM 9020 Program. He is presently the Chief, Navigation Systems Branch in SRDS.

ABSTRACT

A program to determine the feasibility of the NAVSTAR/GPS (Global Positioning System) for use by the civil aviation community is presently being initiated by the Federal Aviation Administration. Such factors as cost to the general aviation user, system compatibility, international acceptance, and minimum performance requirements, related to the pilot workload as well as system requirements, are major factors to be investigated. System alternatives ranging from enhancement of the present configuration to an independent civil transmitter will be developed and evaluated, if necessary. The extent of airborne equipment complexity and the necessity for ground support systems will also be evaluated with respect to cost tradeoffs between the space and user segments. It should be noted that problems such as international acceptance, civil community costs and other institutional problems, requiring extensive inter and intra government coordination are not addressed in this paper.

INTRODUCTION

The present VORTAC system for CONUS operations and the recent replacement of Loran-A by Omega for oceanic operations have been more than satisfactory for air navigation (1). New systems such as NAVSTAR/GPS and Loran-C have been recognized as possible replacements for these current systems due to their inherent advantage of having a global or wide area coverage capability. In addition, these systems could have low operation and maintenance (O&M) cost to the Government due to their inter-modal application and low labor-intensive maintenance requirements.

Both Congress and the Executive Branch of the Government have become concerned with the proliferation of positioning and navigation systems; both in the defense and civil sectors (2) (3). Based on the potential capability of GPS and initial flight tests using the inverted test range at Yuma, Arizona, replacing the approximately 1000 VORTACs could be technically feasible provided that minimum navigation requirements can be provided at a cost acceptable to the civil user community. At present, a general aviation user can be equipped for well under $2000 for IFR operations. Recognizing that the GPS avionics would have increased capabilities, a recent study (4) has suggested that a $2500 figure is necessary by this new technique to be competitive to the present VOR/DME system when user and system costs are totaled.

It is, therefore, very important that the FAA evaluate the range of capabilities of the system now under design by the DOD to determine the minimum required user equipment configuration for general aviation IFR operations. These could range from:

(1) parallel satellite tracking, inertial/baro augmentation, multiple frequency/code equipments and,

(2) single channel, unaided single frequency/code equipments.

Subsequent evaluations must explore the configurations necessary for other operations encountered in the high density terminal and oceanic environments.

BACKGROUND

The NAVSTAR/GPS (Global Positioning System) (5), a "joint" Department of Defense (DOD) program, is the result of the earlier development of the Timation system by the Navy and the 621B system by the Air Force. Phase I initiation was approved by the Defense Systems Acquisition Review Council Review Committee (DSARC) in December 1973 and full operational capability is presently scheduled in the 1985/86 time frame. Figure 1 depicts the official GPS Schedule.

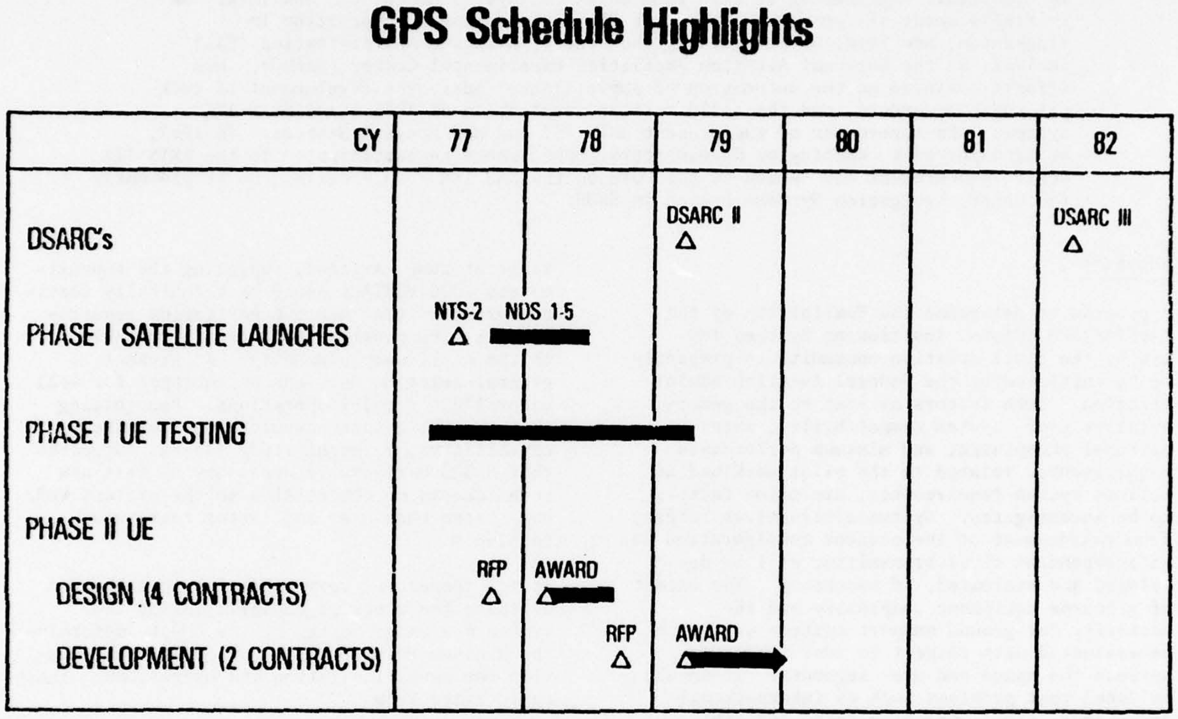

FIGURE 1. GPS SCHEDULE
(Courtesy of Aerospace Corp.)

Space Segment. The presently planned GPS configuration is 24 satellites; 8 satellites in three inclined, 10,900NM, 12 hours orbits (6). Each satellite transmit two psuedo random noise (PRN), spread spectrum, coherent L-band signals. One signal, at the 1575 MHZ, has two quadra-phase modulated sequency of binary digits; the P-code (Precision) is transmitted at 10.23 Mbps and the C/A code (Clear/Acquisition) at 1.023 Mbps. Satellite data is generated coherently with the codes at a rate of 50 bps. These data frames define the satellite emphereris, clock data, identification and status. The second signal is transmitted at 1227 MHZ, but only contains the P-code at this time. It is estimated that from 5 to 9 satellites would be in view to a user at any one time. The availability of the P-code to the civil community is currently indeterminate and various alternatives are being considered. Civil alternatives to this problem are discussed later.

Control Segments. The control segment consists of three passive monitor stations with an additional station, Vandanberg AFB, serving a dual role as the Master Control Station with upload capability to transmit ephemeris and clock correction data to each satellite.

User Segment. At present, three classes of user avionics are being developed in Phase I. Other classes, not intended for aviation purposes are also under development (missile and manpack/vehicular applications). Phase IIA, which is the pre-design phase, has already been initiated and will result in the user equipment specification which would optimize the life cycle costs for multiple host vehicles. Phase IIB will be awarded during the first half of CY-79 and result in pre-production hardware. Table I indicates the types of user equipment developed in Phase I while Table II summarizes the Phase II GPS user equipment.

Phase I DT&E

USER EQUIPMENT

SET	DESCRIPTION	AUX SENSOR AIDING	OPERATING FREQUENCY L1 1575 MHz	L2 1227 MHz	SIGNAL CODE P	C/A	UE CONTRACTOR
X	4 CHANNEL, HIGH PERF	NO	YES	YES	YES	YES	MAGNAVOX
Y	1 CHANNEL, MEDIUM PERF	NO	YES	YES	YES	YES	MAGNAVOX
XA	4 CHANNEL, HIGH PERF	YES	YES	YES	YES	YES	MAGNAVOX
YA	1 CHANNEL, MEDIUM PERF	YES	YES	YES	YES	YES	MAGNAVOX
HDUE	5 CHANNEL, HIGH PERF	YES	YES	YES	YES	YES	TEXAS INSTRUMENTS
MVUE	1 CHANNEL, MANPACK/ VEHICULAR	NO	YES	YES	YES	YES	TEXAS INSTRUMENTS
AFAL/GDM	5 CHANNEL, HIGH PERF	YES**	YES	YES	YES	YES	COLLINS
MP	1 CHANNEL, MANPACK	NO	YES	YES	YES	YES	MAGNAVOX
Z	1 CHANNEL, LOW COST	*	YES	NO	NO	YES	MAGNAVOX
ABU	2 CHANNEL (X-Set)	NO	YES	YES	YES	YES	MAGNAVOX

*ONLY BAROMETRIC ALTIMETER OPTION AVAILABLE

**DOPPLER VELOCITY COMPENSATION AND DIRECTIONAL ANTENNA USED FOR HIGH ANTIJAM

TABLE 1
PHASE I USER EQUIPMENT
(Courtesy of Magnavox and General Dynamics)

Phase II User Equipment

- ACQUISITION PLAN

PHASE	ACTIVITY	SCHEDULE	
IIA	INITIAL DESIGN (4 CONTRACTS)	RFP	SEP 77
		PROPOSALS	NOV 78
		CONTRACTS	FEB 78
IIB	DEVELOPMENT (50-60 sets) (2 CONTRACTS WITH FLYOFF)	RFP	SEP 78
		PROPOSALS	NOV 78
		CONTRACTS	FEB 79 (DSARC II)

PHASE IIA OBJECTIVES

- BALANCE LIFE CYCLE COST (LCC), PERFORMANCE, SCHEDULE
- DESIGN TO LCC NOT TO UNIT COSTS

- PHASE IIA TRADE STUDIES
  - LCC VS UNIT PRODUCTION COSTS
  - LCC VS SYSTEM PARTITIONING
  - LCC VS MODULARITY
  - LCC VS BUILT IN TEST (BIT)
  - LCC VS MTBF
  - LCC VS PERFORMANCE
- PHASE II WILL LEAD TO DEFINITION OF USER EQUIPMENT CLASSES FOR OPERATIONAL SYSTEM

Phase II User Equipment
(Courtesy of Aerospace Corp.)

Of the three systems considered applicable to civil aviation, (X, Y, & Z), the medium "Y" and low "Z" anti-jam receivers are of specific interest to the civil commnity. Basically, the classes of avionics are different due to their complexity. The "X" set can process 4 satellites simultaneously, detect both C/A and P codes, use L1 and L2 for real time correction of ionospheric anomalies, and have the capability to augment the systems with other airborne components such as inertial systems. The "Y" set retains nearly all of the "X" functions except that satellites are processed in a sequential manner. The "Z" set is further simplified in that only the C/A code and the L1 frequency are processed. Figure 2 shows the Magnavox "Z" set designed to replace the Military ARN-118 TACAN by the FAA. This set was chosen for evaluation due to its reasonable availability from a time factor and, its basic configuration would represent the most basic low cost configuration.

PRODUCTS AND EXPECTED RESULTS

The feasibility of using the present GPS configuration for civil applications at an acceptable cost to the user is presently the major FAA goal. An overall program has been established which concerns not only GPS but other navigation alternatives such as the present VORTAC, VLF/Omega, and Loran C systems. Figure 3, Navigation Master Program Chart, depicts this program. It should be noted that the major design milestone is scheduled for 1985. Of course, to reach this point, the FAA must make a number of decisions, not only with regard to the GPS, but also to the other systems. See Figure 3, Page 5)

SET Z NAVIGATIONAL SET

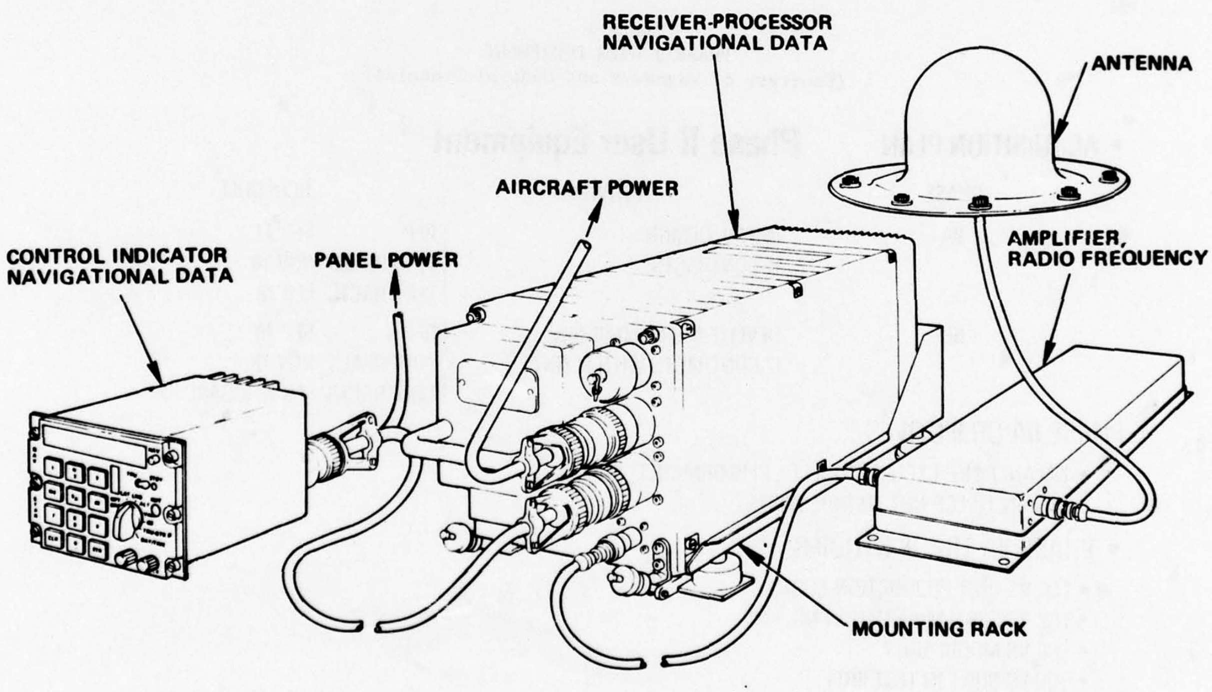

FIGURE 2
"Z" Navigation Set
(Courtesy of Magnavox and General Dynamics)

NAVIGATION
MASTER PROGRAM CHART

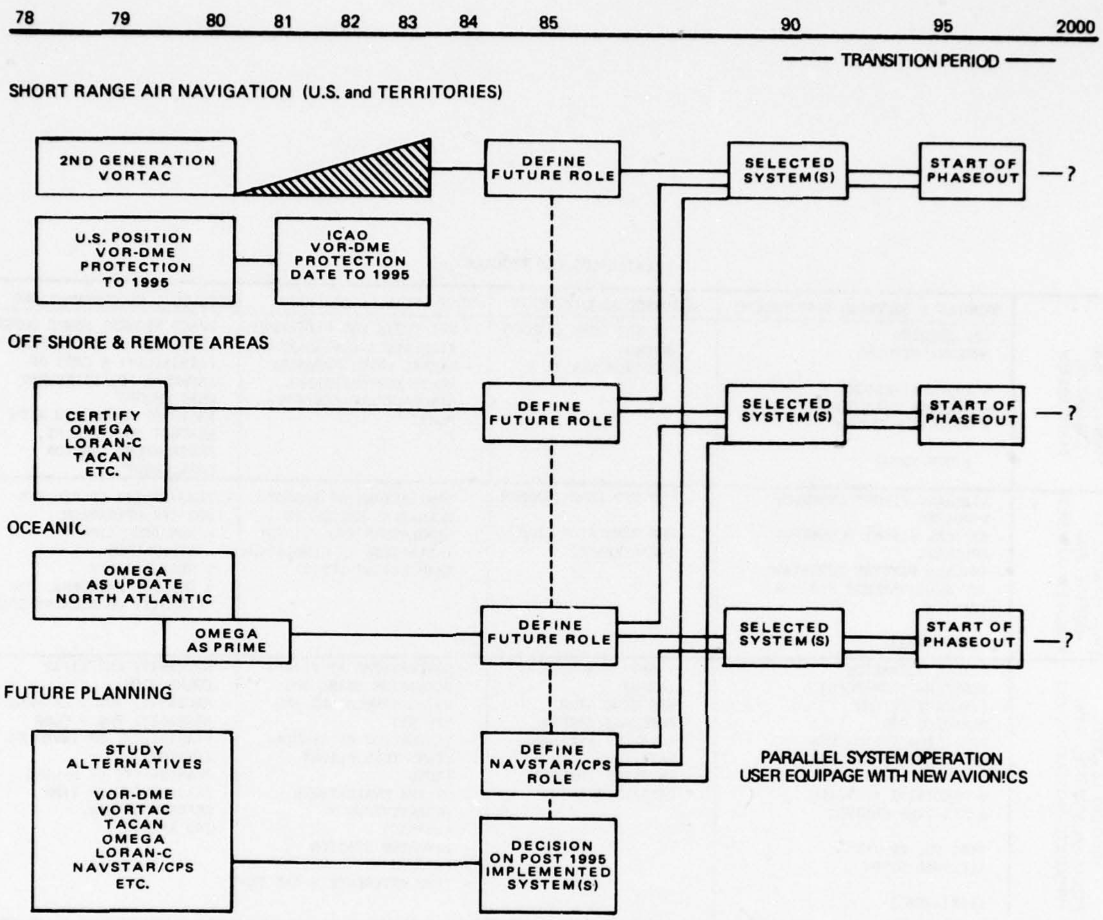

FIGURE 3
FAA NAVIGATION MASTER PROGRAM CHART

At present, two satellites are in orbit and subsequent launches are scheduled for three month intervals, although problems may have arisen, which may cause disruption. Development of the "Y" and "Z" class avionics are also slightly behind schedule. The result of these delays is such that the earliest that FAA can conduct a test and evaluation effort would be during the early summer of 1979. Recognizing these spare and user segment equipment availability problems, the following efforts are being contemplated based on available manpower and funding. Table III summarizes these efforts which supports, as previously stated, the basic object of this program; the development, evaluation, and recommendations of any changes to the present system which would allow significant utilization of NAVSTAR/GPS by the civil air community. (See Table III, Page 6.)

Basic Evaluations

A number of efforts will be immediately instituted which do not require a complete space configuration. The following are examples of tasks which are considered basic to subsequent, more detailed developments.

- Development of Low Cost General Aviation Antennas. This effort is considered very important to the civil community since it could impact on the receiver sensitivity, loop bandwidth, satellite tracking concepts, and navigation software. Poor antenna gains and antenna masking may have serious cost implications. This could effect the radiated power and number of satellite transmitters and, possibly, require multiple receiver channels and supplemental ground stations.

NAVSTAR/GPS R&D PROGRAM

	STUDIES & SOFTWARE DEVELOPMENT	HARDWARE REQUIREMENTS	TEST, EVAL. & ANALYSIS	RESULTS & RECOMMENDATIONS
SIGNAL/ANTENNA EVALUATION BASIC DESIGN	- RFI STUDIES - ANTENNA STUDIES o ANTENNA DESIGNS o ANTENNA SHIELDING o ANTENNA MOUNTING (1978-1979)	- "Z" SET LOAN (SAMSO) - ANTENNA - SPECTRUM ANALYZER	- RFI TESTS FOR DIFFERENT AIRCRAFT & ENVIRONMENTS - SIGNAL MARGIN MEASURE MENTS FOR DIFFERENT AIRCRAFT AND ENVIRON- MENTS	- SPACE SEGMENT POWER BUDGET - NECESSITY OF RF FILTERS - FEASIBILITY & COST OF ANTENNAS FOR DIFFERENT USER GROUPS - RECEIVER BANDWIDTH WITH RESPECT TO AIRCRAFT, ENVIRONMENT, AND/OR USER GROUP
NAS FEASIBILITY ENROUTE/NON-PRECISION APPROACH	- AIRCRAFT FLIGHT DYNAMICS MODELING - TYPICAL FLIGHT SCENARIOS MODELING - ANTENNA PATTERN MODELING - ATC REQUIREMENTS FOR GPS (BASIC) (1979-1981)	- "Z" SET LOAN (SAMSO) - GPS SIMULATOR LOAN (AFAL/WPAFB)	- SIMILATIONS OF FLIGHT SCENARIOS USING GPS SIMULATORS AND "Z" SET - VALIDATION OF SIMULATIONS THRU FLIGHT TESTS	- FEASIBILITY OF "Z" SET FOR IFR OPERATION o NON-PRECISION APPROACHES o TERMINAL OPS o HOLDING PATTERNS, ETC. - NECESSITY OF AUGMENTATION
ADVANCED CONCEPTS PRECISION APPROACH, TIME REFERENCED NAVIGATION, CAS	- FLIGHT SCENARIOS MODELING (ADVANCED) - AIRCRAFT FLIGHT DYNAMICS FOR PRECISION APPROACHES - ATC REQUIREMENTS FOR GPS o PRECISION APPROACH o CAS TIME CONTROL - BARO VS. GPS/MLS ALTITUDE STUDY (1981-1985)	- Y SET* PURCHASE (SRDS) - GPS SIMULATOR PURCHASE (SRDS) - ADVANCED ANTENNAS - DATA LINK - INVERTED (DIFFER- ENTIAL) STATION	- SIMULATIONS AT FLIGHT SCENARIOS USING GPS USING SIMULATORS AND "Y" SET - VALIDATION OF SIMULA- TIONS THRU FLIGHT TESTS - UPLINK EVALUATIONS (CORRECTIONS & ALMANAC) - INVERTED STATION FLIGHTS - TIME REFERENCE & CAS TEST	- NECESSITY FOR L1/L2 CORRECTION - NECESSITY FOR 2 CHANNELS - NECESSITY FOR P CODE - FEASIBILITY OF INVERTED STATION - FEASIBILITY OF UPLINK - FEASIBILITY OF TIME REFERENCED NAV. (4D RNAV)

6/23/78

*This set will be capable of being configured from a single channel, one frequency, C/A only code device to a two frequency, C/A & P code device using augmentation and variations in between.

TABLE III
FAA NAVSTAR/GPS R&D PROGRAM

o RFI tests. Interference, both external and internal to aircraft is obviously critical to signal-to-noise ratios and, in turn, to receiver design. Tests will be performed in high density areas in various aircraft to determine the extent of this problem. It should be noted that, more often than not, antenna and noise problems have been prevalent in past development of radio navigation systems. Again, satellite power and ground augmentation stations may be tradeoffs to be considered in lieu of an alternate signal structure as recommended in past studies (7). Both spectrum analyzers and the "Z" set will be used in these tests, both in a static and dynamic flight modes.

o Flight Scenario Modeling. In conjunction with the use of actual hardware and a GPS simulator (8), typical flight scenarios shall be developed using non-precision approaches to selected airports in the vicinity of NAFEC and other test ranges as well as high noise environments in the Northeast Corridor. These scenarios will be predicated on the final satellite configuration, but will consider the limitations of the number of available satellites at the time of flight testing. These flight tests shall validate these simulations and allow evaluation of stress conditions that could be prevalent when a full satellite constellation is operational.

Enroute/Non-Precision Approach Evaluations

Most FAA regulations and procedures are based on the unique characteristics of the present VOR/DME system. The following tasks are intended to identify any problems inherent in transitioning to this new technology and recommend changes to both the air traffic control and navigation systems.

- Aircraft Flight Dynamics Modeling. Such factors as antenna masking by aircraft structural members and the required update rates for the navigation software may be significantly influenced by different aircraft flight dynamics. This effort will use the products of the previous antenna and flight scenario projects as well as determine the necessity of receiver aiding such as baro altitude.

- ATC Requirements for GPS (Basic). Present ATC procedures and avionic requirements have been predicated on the use of a large number of VOR/DME stations. This requires a minimum of pilot workload for station selection and identification as well as course (bearing to station) setting. Controllers also use these VOR/DME stations or selected radial intersections as references. Aircraft maneuver or aircraft attitude has little effect on displayed cockpit information and navaid failures are easily detected by the current system. Ground system failure does not effect large numbers of aircraft and the redundancy inherent to the VOR/DME system allows easy transition to nearby facilities. Therefore, flight technical error, pilot workload and blunder rate, through common usage, have become recognized, but not necessarily quantitied factors.

NAVSTAR/GPS, being a pure area navigation system (RNAV), which uses steering commands to a flexible waypoint system, and not radials to fixed ground stations, does not enjoy this advantage. Failure modes, ground and airborne equipment monitoring, data entry, data update and display as well as other operational factors, which impact on the acceptability of a navigation system, must be evaluated. To define these factors and quantify their significance with respect to the present rho/theta system, enroute and terminal IFR operations will be flown and analyzed as well as non-precision approach procedures. Figure 4 shows the front panel layout of the Magnavox "Z" set which will obviously require considerable pilot workload. These efforts will be conducted in a time frame which will allow a basic understanding of the suitability of GPS to the civil air community by the end of CY-79. At that time, critical issues will be defined and R&D efforts to overcome these problems will be initiated.

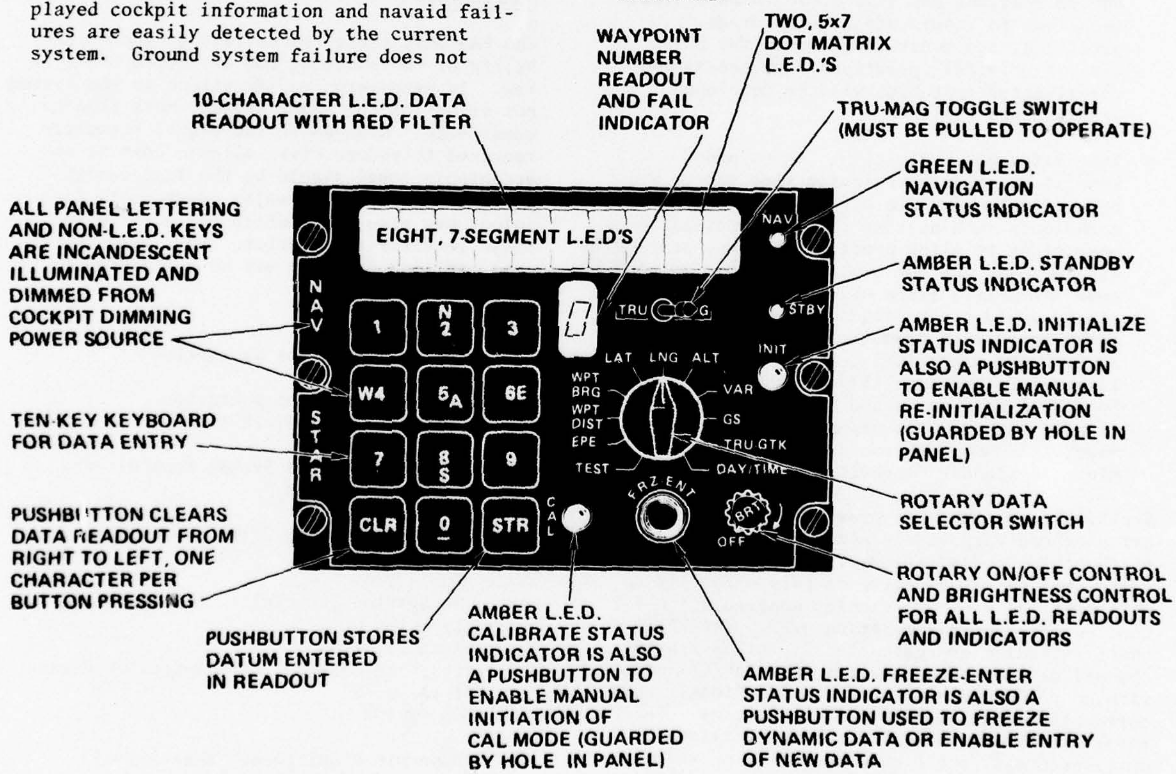

FIGURE 4
"Z" Set Front Panel

Advanced Concepts Evaluation

The previous efforts may indicate that the low cost, general aviation avionics may not be sufficient for high density operations. In addition, the inherent precise worldwide time source could be a more important factor than the primary GPS navigation capability. As a result, a more flexible airborne receiver presently classified as the "Y" set (see Table I) will be purchased and evaluated. This receiver will allow both P and C/A code acquisitions and L1/L2 processing to allow phase delay correction to satellites at low elevation angles. The high dynamics of terminal operations and antenna limitations may require this capability. The necessity of multiple channel operations will also be determined as well as the benefits of augmentation.

- Ground Augmentation/Monitoring. Recognizing that the cost of avionics may be prohibitive (more than $2500) so that the previously mentioned problems can be minimized, ground augmentation to the space segment may be developed and evaluated. The use of an uplink to transmit phase correction, almanac, and waypoint information could be a major cost beneficial approach and possibly the only way to insure low cost avionics. Inverted stations may also prove to be a viable technique to insure adequate coverage, precision, and monitoring needed for high density terminal operations. If necessary, experimental test beds will be developed and concepts evaluated.

- Time Reference Evaluation. As an added benefit, a precise worldwide time source will be available as a GPS by-product. Therefore, techniques such as time reference navigation operations to allow precise metering, station keeping, and CAS for CONUS operations may become attractive since expensive airborne clocks would not be required. Also, in combination with communication satellites or high frequency (HF) communications, a time referenced surveillance technique could be viable for remote and oceanic applications. Although not primary surveillance mode, this approach could be valuable to minimize blunder detection.

Technical Approach: As previously stated, GPS avionics can vary widely according to the number of channels, codes, frequency, and augmentation. Again, the basic objective of this effort is to establish the minimum avionics configuration for the low cost general aviation user. The FAA shall initially evaluate the "Z" set; a single channel device which utilizes only the C/A code with no real time atmospheric corrections. Such corrections require both GPS frequencies. Later efforts will utilize a "Y" set which allows multi-frequency and P code operation as well as aiding inputs such as baro-altimeter.

Status and flight tests will be performed at NAFEC and other appropriate locations to establish RFI and signal strength levels. In parallel to this effort, antenna development, aircraft scenario and aircraft dynamics modeling will be initiated to allow simulation with the various GPS simulators (evaluators) now being developed by DOD. Base line flights at Yuma will also be performed to establish the credibility and validate flight and simulation tests.

Depending on the results of the above efforts, uplink data experiments for the transmission of almanac data, atmospheric phase correction, and any other technique to minimize user cost will be attempted. Inverted stations to improve precision and serve as monitoring stations will also be considered.

SUMMARY

Due to the relatively recent availability of signals, most FAA efforts have been directed to the analysis of the economic consequences of utilizing GPS (4). These studies have shown that the most sensitive factor in the acceptance of GPS as a VORTAC replacement for civil applications is the cost of the user avionics.

CONCLUSIONS

The FAA must first concentrate on the suitability of the existing DOD developed GPS system. If necessary, modifications to the system not effecting the space segment must then be considered. Changes to the signal structure required to reduce civil avionic cost to an acceptable level should be the last resort. It is recognized that major advances in technology may also occur which could solve the basic receiver cost factor. But, even in this case, antenna problems may be a limiting factor.

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FAA SRDS AIR TRANSPORT COCKPIT ALERTS/WARNINGS STUDIES

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BIOGRAPHY

John F. Hendrickson received his B.E.E. degree in 1956 from C.C.N.Y. and his M.S.E.E. degree from M.I.T. in 1959. He was a member of the M.I.T. research staff at the Instrumentation Laboratory (now Draper Laboratories) and the Measurement Systems Laboratory where he was involved in the development of prototype inertial navigation systems, sensors and components. He subsequently joined the NASA Electronics Research Center where he participated in feasibility studies of strapdown inertial systems using redundant sensors and Laser gyroscopes. He came to the FAA SRDS in 1970, where he has been occupied, inter alia, with alert/warning system requirements since 1971. He is a member of Eta Kappa Nu, Tau Beta Pi and Sigma Xi. He co-holds a patent and is a Professional Engineer registered in New York.

ABSTRACT

The indiscriminate proliferation of alerts, cautions and warnings may be approaching the saturation level of the flight crew under heavy workload. With the designs of new air transports, it is desirable to encourage the airframe manufacturers and the operators and users to make an integrated approach to the design of the alerting system to develop a functionally standardized system. The Federal Aviation Administration (FAA) has initiated a developmental program which utilizes Government and industry resources to produce guidelines and criteria for an air transport cockpit alerting system. This paper presents a brief discussion of the approach and analysis of results of the preliminary stages of this program. Detailed results are to be found in the references.

The first phase of this program produced two sets of conclusions as a result of an analysis of data collected relative to (1) the alerting situation in current air transport cockpit, and (2) human factors testing appropriate to alerting devices.

These conclusions represented a general set of recommended design guidelines:

o A consistent design philosophy that can be applied to all new aircraft irrespective of manufacturer.

o Relatively quiet, dark cockpit when all systems are operating normally and when abnormal situations have been cleaned up.

o Associate a unique, audio, visual or combination audio-visual method of alerting with each alert priority level.

o Provide alerting system growth capability in a form that does not necessitate additional discrete annunciators.

In addition to these general design guidelines more specific human factors guidelines were developed.

Future activity of this program will encompass the development of candidate alerting system concepts, their implementation and evaluation in appropriate flight simulators. The criteria for the system evaluation is being developed jointly by the Man-Vehicle System Division of NASA Ames Research Center and the FAA.

a. BACKGROUND: The FAA in the early seventies began examining the current alerting system situation in the air transport cockpit with the aim, at this time, of proposing a unique, or, at least, a dissimilar alert for an independent altitude monitor system [1, 2]. It was evident that the increase in number of alerts, cautions and warnings that have developed with each succeeding generation of modern aircraft would hinder the introduction of any new alerting requirement. The FAA made the decision to examine the total alert/warning situation and eventually to develop a functionally standardized system.

b. TECHNICAL APPROACH: The first step in the characterization of the alert/warning environment was performed in an FAA directed study [3] of the air transport cockpit environment. In this study, current operational manuals for numerous aircraft types were searched for alerting functions. The alerts were classified according to type, i.e., warning, caution, and advisory. These tabulations were then reviewed and analyzed to determine what, if any, correlations exist. Figures 1 and 2 are some typical data obtained as related to the different types of aircraft.

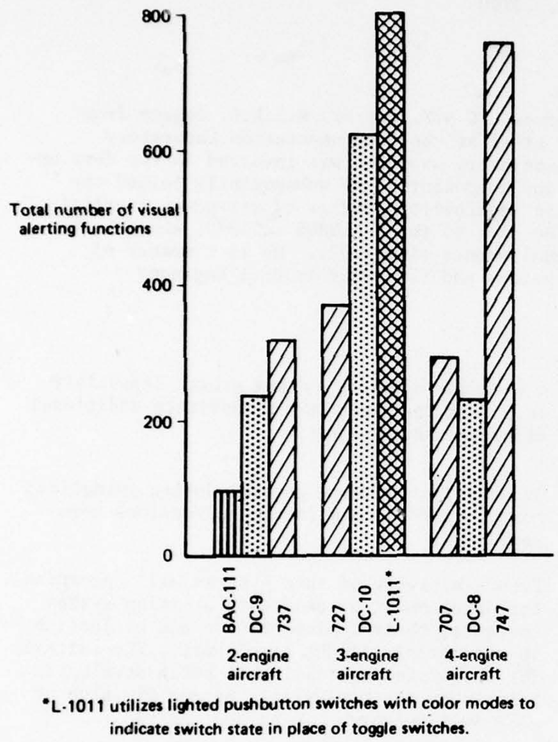

FIGURE 1. NUMBER OF VISUAL ALERTING FUNCTIONS ON EACH BASIC AIRCRAFT TYPE

Figure 1 shows the relationship between the number of visual alerting functions versus aircraft type and recency of design. The three most recent designs which are also the wide-bodied designs, have the highest number of visual alerting functions. The causes are partially related to regulatory requirements for more alerts, and to the wide-bodied design which necessitated lighter more complex subsystems making more alerts mandatory for operational safety.

Figure 2 categorizes the alerting functions into warnings, cautions, and advisories and relates these to design year (year of first flight) of each type of air transport. Again the most recent designs which are are the wide-body aircraft show the highest numbers. The warning functions increased a smaller percentage than either the cautions and advisories. This can be explained by the increase in the need for display of maintenance and operational information by the user. This is at the discretion of the operator whereas the warning functions are more closely tied to the regulations.

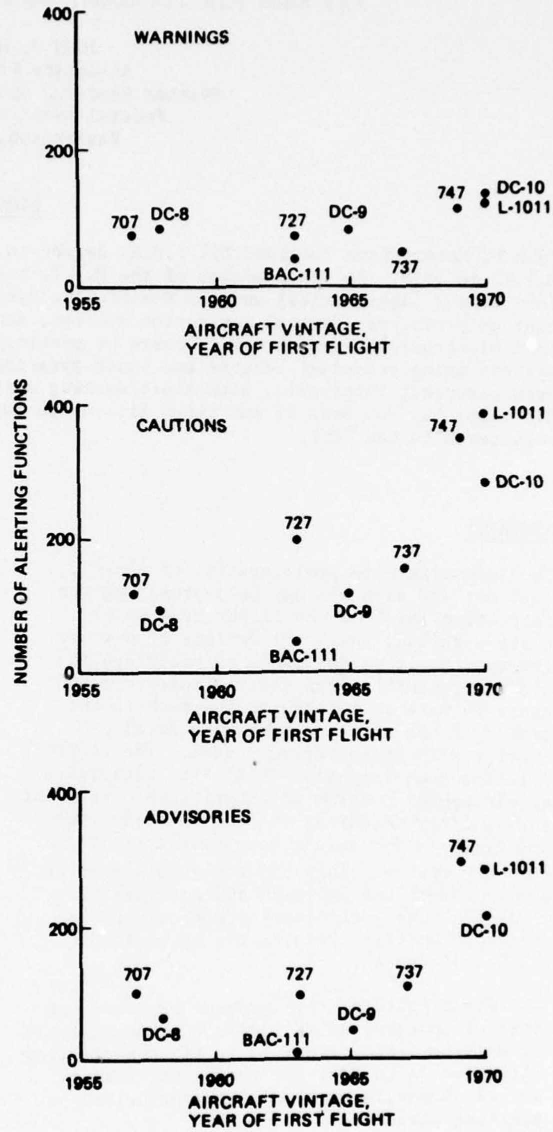

FIGURE 2. APPLICATION OF ALERTS AS A FUNCTION OF OPERATIONAL SIGNIFICANCE AND AIRCRAFT VINTAGE

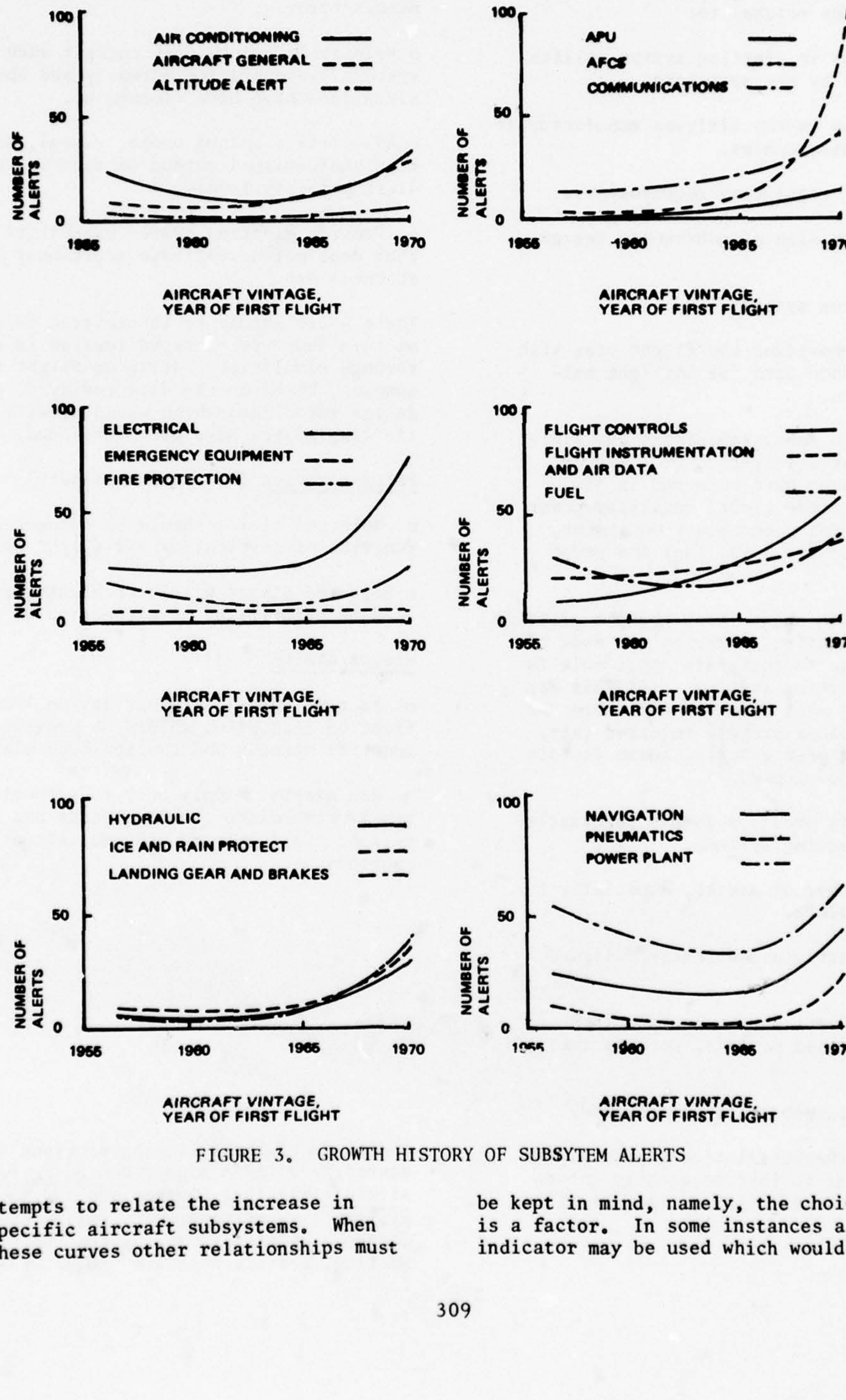

FIGURE 3. GROWTH HISTORY OF SUBSYTEM ALERTS

Figure 3 attempts to relate the increase in alerts to specific aircraft subsystems. When examining these curves other relationships must be kept in mind, namely, the choice of display is a factor. In some instances a dial type indicator may be used which would not be

classified as an alert whereas a light would be classified as such. Therefore, those classes of subsystems which over the years, changed from dials to lights show an upward trend in their curves, for example the electrical subsystem vs. the hydraulic subsystem.

c. SUMMARY. In summary, some general statements can be made to characterize the current alerting system situation:

o The increase in alerting systems with each new aircraft can be related to:

1. Differences in alerting system utilization philosophies by the operators.

2. Differences in the airframe manufacturers cockpit design philosophies.

3. Additional regulatory requirements.

4. Increase in size of subsequent design aircraft.

5. More complex systems.

o The trend to providing the flight crew with improved maintenance data for inflight malfunction diagnosis.

o Rapid growth in subsystem alerts for electrical and automatic flight control system. Negligible increases have occurred in air conditioning, altitude alert, auxiliary power units, communciations, emergency equipment, flight instrument, air data, fuel and power plant systems.

In conjunction with the current cockpit alerting system characterization, a review was made of the existing human factors data applicable to the design of alerting systems. [4] This was done to determine what data was available and tests to obtain other propose required data. Without repeating past efforts, human factors guidelines were developed.

A survey of pilots provided issues relevant to the design of alerting systems.

o Reduce the number of alerts, especially the number of aural alert.

o Most aural alerts, as currently designed, are too loud.

o Noncritical alerts should be inhibited during high-work-load periods, such as take-off and flare/land.

o Selected alerts should be prioritized.

o Audio-visual characteristics of the alerts should be designed to instantaneously inform the pilot of the criticality of the situation.

o Direct correlation between the type of alerts and the type of checklists should be established, i.e., warnings and emergency checklists, cautions and abnormal checklists, etc.

Recommended Design Guidelines:* As a result of the reviews and surveys, the following general types of goals for the alerting system characteristics and cockpit environment were developed:

o A consistent design philosophy that can be applied to all new aircraft, irrespective of manufacturer.

o Relatively quiet, dark cockpit when all systems are operating normally and when abnormal situations have been cleaned up.

o Associate a unique audio, visual, or combination audio-visual method of alerting with each alert priority level.

o Provide alerting system capability in a form that does not necessitate additional discrete annunciators.

These goals should be interpreted as guidelines at this juncture since validation is required through simulation testing or flight testing; however, based on the data reviewed, preliminary design guidelines which would provide such an alerting system have been developed.

Prioritization (If found necessary)

o Selected alerts should be categorizes as a function of criticality and flight phase.

o Selected alerts within each category might also be prioritized as a function of criticality.

Visual Alerts

o An alphanumeric readout device located in front of each pilot should be provided to identify warning and caution-type alerts.

o Red Alerts: Apply only to situations that require immediate crew awareness and eventual action; i.e., only to abnormal situation or cautions.

*Portions of the following sections were presented in an AIAA paper, Design Criteria for Aircraft Warning, Caution and Advisory Alerting System, J.E. Veitengruber, Boeing Commercial Airplane Co, AIAA Aircraft Systems and Technology Meeting, Seattle, Washigton August 22-24, 1977

o Amber/yellow alerts: Apply only to situations that require immediate crew awareness and eventual action; i.e., only to abnormal situation or cautions.

o Green alerts: Use to confirm the SAFE OPERATION or GO status of a system.

o Blue alerts: Use to annunciate in transit conditions (or as the basic color associated with all advisories; i.e., only advisory situations.

o White alerts: Use for illuminating keyboards and annunciating ON/OFF system modes; i.e., when used in place of toggle switches.

o Location:

o Warning devices should be located within 15 degrees of the pilot's centerline of vision (centerline of vision is defined as the line between the pilot's eye reference point and the center of the ADI).

o Caution devices should be located within 30 degrees of the pilots centerline of vision.

o Green, blue, and white lights can be located anywhere in the cockpit that is readily visible to the crew.

o All alerts presented by discrete, lights, flags, or bands should be repeated on the alphanumeric readout device (except automatic flight-mode annunciators.)

o Brightness: Automatic brightness adjustment for varying ambient light conditions should be provided.

o Flashing: Use only for highest priority Warning alerts.

Aural Alerts

o Application: Use discrete aural alerts to annunciate highest priority situations and to attract attention to caution alerts on the alphanumeric readout device.

o Maximum Number:

o Less than four familiar alerts (based on pilot opinion)

o If the number of discrete aural and tactile alerts exceeds seven, they should be supplemented by voice annunciations.

o Intensity:

o Maximum intensity of 15 dB above threshold noise level or halfway between threshold level and 110 dB, whichever is less.

o Automatic intensity adjustment for varying ambient noise conditions should be provided.

o Total cancellation of aural alerts associated with warning items without correction of the fault or situation should be prohibited; however, a means of reducing the annoyance of continuous aural alerts after initial recognition is achieved should be provided.

o A means of disabling any nuisance actuation of aural alert should be provided in a form that does not affect the integrity of the other aural alerts; e.g., one circuit breaker or guarded/wing shutoff switch for each aural alert.

o Sound Characteristics:

o Each signal should be composed of two or more widely separated frequencies in the range from 250 to 4000 Hz

o Intermittent signals should be used.

o Voice Characteristics:

o Messages should be preceded by an identifier to which the pilot is more than normally sensitive (attention-getter).

o Messages should be constructed of short sentences of polysyllable words.

o Pilots should be familiar with all voice messages.

Tactile Alerts

o Minimize use of tactile alerts.

Master Warning/Master Caution

o A master warning signal and a master caution signal should be located in front of each pilot if the alphanumeric readout is located outside the pilot's primary field of view.

All warnings should activate the master warning signal (if used).

o All cautions should activate the master caution signal (if used).

o No advisory or status alerts should activate the master warning or master caution signals (if used).

Checklist Correlation

o Type of alert and type of checklist used to rectify an annunciated situation should be correlated.

o Emergency procedures should be assocated with warning-type alerts.

o Abnormal procedures should be associated with caution-type alerts.

NOTE: A checklist is not necessarily associated with each warning or caution item, and an alert

is not necessarily associated with each checklist.

In conclusion, these guidelines must be subjected to extensive testing both at the system and subsystem levels to verify the design philosophies. Human factors analyses are required to determine the operational characteristics of the hardware implementation. The FAA is proceeding with a cooperative effort with a group of aircraft manufacters of perform the required tests and analyses.

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EVALUATION OF HEAD-UP DISPLAY FOR CIVIL AVIATION

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BIOGRAPHY

William B. Davis, Jr. is a 1956 graduate of the University of Washington, Seattle, Washington, in Aeronautical Engineering. Prior to that, Mr. Davis spent 5 years as a carrier fighter/attack pilot in the U.S. Navy. After graduation, Mr. Davis joined the Northrop Aircraft Corporation as an aerodynamicist. In 1958, Mr. Davis re-entered the Navy where his duties included tours as a fighter and attack pilot aboard carriers, a flight instructor in the Naval Air Training command, and a radar air control officer aboard ship. In 1965, he joined the McDonnel Aircraft Corporation in St. Louis as a Senior Flight Test Engineer. In 1967, Mr. Davis graduated from the U. S. Air Force Aerospace Research Pilot School Experimental Test Pilot Course, at the Air Force Flight Test Center, Edwards AFB, California. Prior to joining the staff of the FAA Systems Research and Development Service in Washington, Mr. Davis spent 7 years as an Engineering Flight Test Pilot in the FAA Eastern Region. Since joining SRDS in 1974, Mr. Davis has worked with the FAA all weather landing program airborne systems as an evaluation pilot and project manager.

ABSTRACT

The performance of the Head-Up Display (HUD) and its effect on the conduct of all weather flight operations in the approach and landing phase are being examined in critical detail in laboratory, simulation and flight tests. The primary emphasis of this evaluation is safety related and concentrates on the contribution of the HUD to flight safety in the operation of large turbojet aircraft. Other factors such as installation and maintenance costs, reliability requirements, and cost effectiveness will not be addressed at this time.

The essential elements of the HUD evaluation program consists of a literature search and background review, a series of related basic laboratory and simulation experiments, a full crew operational simulation evaluation and demonstration, and a flight test program consisting of an engineering evaluation and a flight demonstration program. Simulation and laboratory experiments are presently underway at the National Aeronautics and Space Administration (NASA) Ames Laboratory. Flight testing will be planned and conducted at the FAA National Aviation Facilities Experimental Center (NAFEC) during FY-80.

The literature search and background review (ref 2) recently completed, concluded that HUD has the potential of aiding the crew by reducing the cockpit workload, increasing instrument reliability, achieving redundancy of information for navigation, flight path control and other tasks, but that additional research is needed to define and document the advantages and disadvantages.

Funding and manpower constraints will limit this evaluation to the approach and landing phase only. Further, these constraints will limit the evaluation of the HUD concept to its interrelations with current conventional cockpit instruments only. At some future date, serious consideration must be given to the concept of a totally integrated electronic cockpit display system evaluating the role and concept of the HUD as an integral part of the total all weather landing system.

BACKGROUND

This project was initiated by letter from the FAA Flight Standards Service Director (AFS-1) dated April 20, 1976, requesting that the FAA Systems Research and Development Service (SRDS) perform a research, development, and evaluation program of the Head-Up Display concept and to determine its contribution to safety in the operations of large turbojet transport airplanes during approach and landing. In a letter dated September 2, 1976, the FAA Administrator requested that the National Aeronautics and Space Administration join FAA in the cooperative effort to investigate the safety potential of HUD. As a result, Task Order DOT-FA77WAI-725 to Inter-Agency Agreement NASA-NMI-1052.151 identifying the extent and the scope of the work to be performed was approved on March 9, 1977.

The primary objective of the Head-Up Display Evaluation Project is to determine the contribution, if any, of a HUD to aviation safety in the form of improved performance in the operations of large turbojet aircraft during approach and landing. To accomplish this objective, consideration will be given not only to the possible benefits of a HUD, but also to the possible limitations that may arise and to any possible detrimental effects or hazards that a HUD may create in the operational environment.

INTRODUCTION

Approach and Landing accidents continue to occur in air carrier operations in spite of considerable technological improvements in the field of approach guidance systems and in spite of a continuous upgrading of cockpit procedures and crew coordination. Factors such as the increasing number and complexity of cockpit instrument displays, transition to high performance aircraft, and the lowering of the landing weather minima, have in the past decade increased the demands placed on the flight crew. These factors, combined with the increased volume of air traffic in the terminal areas, and increasingly complex air traffic environment, have added significantly to the workload in the cockpit.

A recent National Transportation Safety Board (NTSB) survey of low visibility approach and landing accidents and incidents from 1968 through 1972 (ref 1) revealed that 47% of the air carrier landing accidents occurred during precision Instrument Landing System (ILS) approaches. More recently, a survey of 17 ILS approach accidents and incidents during the years 1970 through 1975 disclosed that almost every mishap occurred after the flight crew had seen the ground, approach lights or runway scene. In several cases, this study disclosed that the pilot(s) had trouble in visually judging the flight path or the descent angle, particularly in low or obscured visibility. While there is an urgent need to explore those factors affecting the aircraft and its crew performance, considerable controversy still exists as to which factors are primarily responsible for these approach and landing accidents. This National Transportation Safety Board accident survey (ref.1) cites human error as the primary cause for most approach and landing accidents. However, in rebuttal, pilot organizations, while admitting some partial pilot factors, claim that the real culprit is poor cockpit instrument format and location. In the landing task where there is little margin for error, the crew may not have sufficient time to adequately evaluate both instrument and visual cues at the decision height when using today's conventional aircraft instruments and when following currently established flightcrew procedures. They also cite shortcomings in the design of conventional cockpit instruments contending that they do not provide adequate cues for rapid detection of glide path dispersions. The difficulty that pilots have in rapidly detecting and correcting dispersions caused by wind shear or turbulence when using conventional displays, the presence of visual cue illusions, and the lack of vertical guidance cues when reverting to head-up viewing (particularly at night), are also cited as major problem areas.

Inadequate time for the pilot to assess the outside visual cues from decision height (DH) to touchdown in low visibility is often cited as one of the more significant problem areas in the see-to-land concept. Some studies have concluded that four or five seconds may be required for a pilot to refocus his eyes and transfer his attention from head-down instrument guidance to the head-up position before he can accurately assess the visual scene. This suggests that the aircraft may possibly descend below the DH for as long as 4 or 5 seconds before the decision to land or go around is made. If so, the margin of error is further degraded. However, this assumption may or may not be valid, because the decision making process is an accumulative one, continuing throughout the approach for some time prior to arrival at the decision height. The need for one crewmember to monitor the flight instruments throughout the approach is well recognized as a desirable safety procedure; however, there is evidence that this procedure is not always being followed, particularly after the first visual cues appear during the approach. A recent USAF study concluded that once the ground or runway appears there is some reluctance to return to the cockpit instruments, even when encountering marginal visibility later in the approach.

Research must continue into means of optimizing crew procedures and refinement of present day instruments in the hope of determining more efficient and safe means of operating with today's conventional electro-mechanical instrument systems. In the meantime, serious consideration must be given to the more flexible advanced electronic display systems which may offer the crew a more precise and efficient means of performing the landing task.

A proposed alternative to conventional cockpit flight instruments is the Head-Up Display, an electro/optical system which displays instrument guidance information collimated to infinity on a semi-transparent glass combiner plate located above the instrument panel in a direct line with with the pilot's view of the outside world. (Figure 1 and 2)

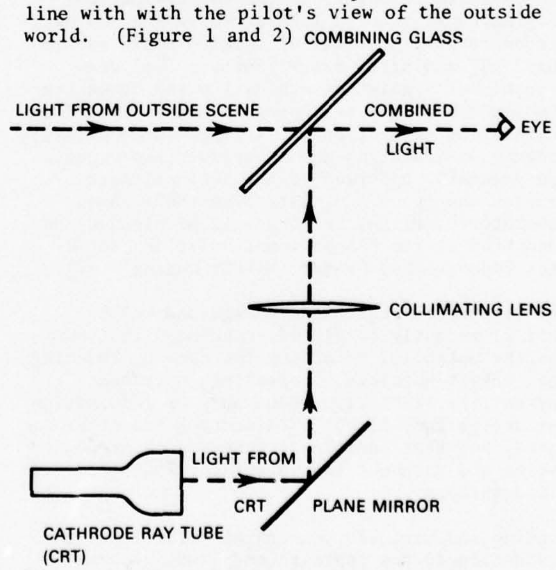

Figure 1. Head-Up Display Optical Path

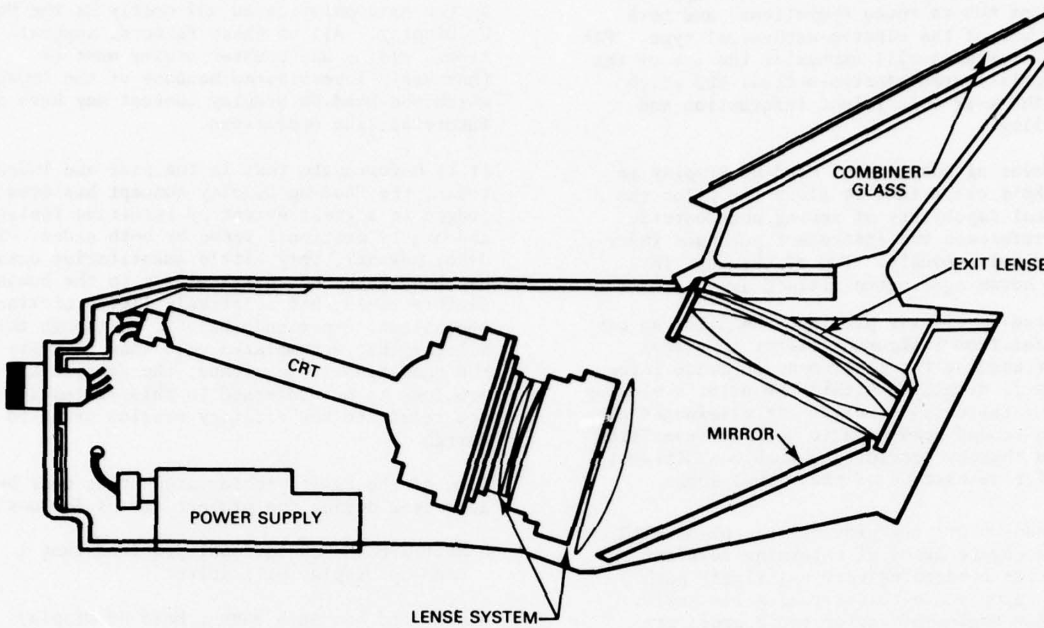

Figure 2. Pilot Display Unit with Folded Optics

Electro-optical Head-Up Displays have been used for a number of years by the military in single piloted fighter and attack aircraft. However, these systems were designed primarily for track computing and delivery of air-to-air and air-to ground weapons, with only secondary use for approach and landing. Initial development of military HUDs paid scant attention to the human factors aspects which today play such an important factor in both military and air transport crew system design. Still, the evolutionary process of the original military HUDs has developed today's HUDs into highly sophisticated weapons delivery systems which have proven to be highly successful (and well liked by the pilots). (Fi

Since 1974, one French domestic airline, Air Inter, has been operating successfully in Category III weather with a fail-passive single channel autopilot backed by an electromechanical HUD used for monitoring and for takeover in event of autopilot disconnect. (Ref. 3). Pacific Western Airline (PWA) of Canada, utilize the Sundstrand Visual Approach Monitor (VAM), an electromechanical HUD, in 7 aircraft on their cargo routes in the artic region. VAM provides the crew with accurate vertical guidance (flight path angle) in the bad weather conditions, unimproved terrain, and poorly instrumented runways PWA operates from in the Northwest Territories. (Ref. 4).

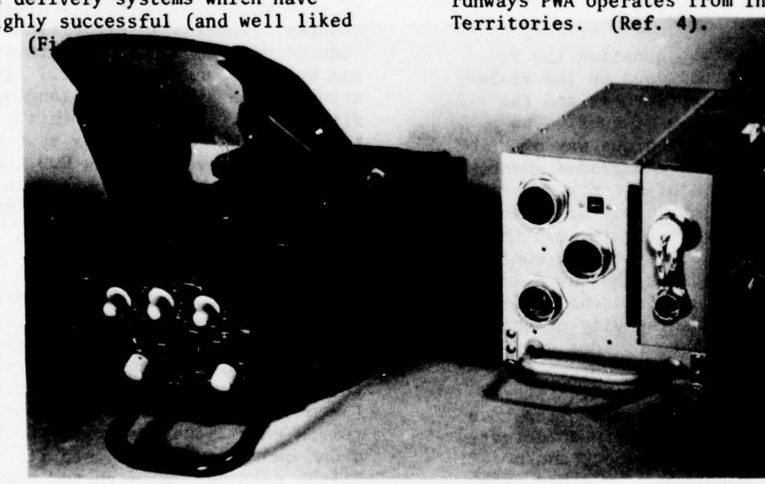

Figure 3. Typical HUD Display Unit with Symbol Generator

To date then, only two airlines have approval for use of HUD in route operations, and both systems are of the electro-mechanical type. FAA and NASA research will emphasize the use of the more sophisticated electro-optical HUD which offers the user more flight information and flexibility.

Those favoring adoption of Head-Up Display in the cockpit claim that it gives the pilot the additional capability of seeing both outside visual reference and instrument guidance information simultaneously. Two of the most important advantages often claimed are:

o The Head-Up Display provides the pilot an easy transfer from instrument flight to visual flight because the instrument guidance information is displayed within the pilot's viewing area of the outside world. It eliminates the 4 or 5 second head-down to head-up transition period thereby providing valuable additional time for assessment of the visual scene.

o The Head-Up Display provides the pilot with a more accurate means of obtaining relevant information concerning vertical flight path guidance on a one-to-one real-world scale. Sighting angles of one or two degrees are readily discernible on the one-to-one scale of a HUD but cannot necessarily be detected easily on panel instruments. This allows better detection of vertical flight path deviations thus decreasing the probability of under-shooting and over-shooting the runway.

The Head-Up Display concept is not without its critics who point out that today's approved approach and landing operations are more than adequate for conducting safe transport category all-weather operations, and have been so proven over the years. To date, there have been no recorded accidents in certified Category II operations. The present concept for Category IIIA calls for a fully automatic approach and landing, which could well reduce the role of a HUD system to that of a monitor.

There are other critics who question the reliance upon external visual cues in low visibility because of the deceptiveness and the difficulty in interpretation of cues. The HUD's combiner glass has no unique way of increasing visual acuity in a degraded scene, other than by the addition of a contact analog runway scenario. The question may be raised "Does the Head-Up Display really improve the pilot's performance in the see-to-land concept, assuming that a few seconds may be saved in the assessment time, if the outside scene is degraded by the reduced transmissivity of the optics that are used?" There is some evidence that the added symbology on the HUD combined with the outside scene may distract, distort, or otherwise divide the pilot's attention to a point where he may lose the ability to detect important changes in both instrument and/or outside visual cues. There may be other arguments, both pro and con, that must be addressed prior to the acceptance of an airborne display system as sophisticated and costly as the Head-Up Display. All of these factors, suppositions, claims and counter claims must be thoroughly investigated because of the impact which the Head-Up Display concept may have on future airline operations.

It is unfortunate that in the past and indeed, today, the Head-Up Display concept has been judged to a great extent by intuitive feelings and highly emotional views by both sides. To date, however, very little quantitative data has been gathered, particularly in the human factors field, and relatively little airline operational experience exists. Although the military has accumulated more than 10 years of HUD operational experience, the particular problems to be addressed in this evaluation do not relate to the military mission oriented HUD design.

Some of the basic problem areas that must be addressed during the project are as follows:

o What are the operational problems that a Head-Up Display will solve?

o What and how much does a Head-Up Display contribute to aviation safety?

o Will the use of a Head-Up Display create some new problem area(s) not previously encountered, and what will the human reaction be to these conflicts?

o In what role(s) will a Head-Up Display enhance operational performance, and how effective is it?

This evaluation project must, by necessity, be heavily oriented toward gaining a better understanding of the various human factor relationships which exist between the crew and the HUD system. It will explore some of the more familiar human factors concepts such as crew workload, cockpit coordination procedures, visual illusory effects and system-induced problem areas. As stated before, time and manpower constraints will limit the evaluation to the approach and landing phases of flight only. The goal of this project is not to develop HUD hardware or system design criteria but to evaluate the HUD concept, as to its influence on human performance in the cockpit and its contribution to aviation safety.

PROJECT DESCRIPTION

The specific HUD evaluation project which is outlined in the following section will investigate the advantages and disadvantages of the head-up display concept in operations of large turbojet aircraft during approach and landing. Factors such as easing the transition from IFR to VFR conditions, reducing touchdown dispersions on short runways, stabilization of the flight path on precision and non-precision approaches, and detecting and coping with wind

shear will be addressed. The project will yield sound objective data relating HUD optical, perceptual, and human factors characteristics to aircraft control under operational conditions. These data will be of benefit to both the FAA and the civil and military aviation community.

The following paragraphs will describe three parts of the project consisting of a background review, basic laboratory and simulation experiments and a full crew operational simulation evaluation. A schedule of activities is described in Figure 1.

Part I: A comprehensive background review and documentation was conducted jointly by FAA and NASA. This review has provided the experimenters with the latest information on the state-of-the-art of both military and civil HUD hardware and will provide the rationale for determining the selection and priority of the specific items to be addressed during Parts II and III that follow. It will also serve as a current status document of past HUD research efforts and will prevent needless duplication. FAA has published Report No. FAA-RD-78-31, titled, "Head-Up Displays: A Literature Review and Analysis with an Annotated Bibliography." (Ref. 2).

Part II: This part comprises the basis laboratory and simulator tests on HUD concepts and is being conducted by NASA/Ames Research Center. It includes questions which have not yet been addressed by others or which require further investigation as indicated by the review. These initial studies will provide data for the selection of the most potentially adequate candidate Head-Up Display. A candidate head-up display is defined as an optical device whose display characteristics have been shown to contribute to the most efficient all around pilot control of his aircraft during approach and landing under operational conditions.

Part III: Will consist of a full crew operational simulation evaluation of the candidate HUD under conditions as close to the operational environment as possible, comparing pilot performance both with and without the use of the HUD. Accomplishment of this part of the effort will be the responsibility of NASA/Ames Research Center.

<u>PART I. HUD BACKGROUND REVIEW</u> - FAA-RD-78-31 (Ref. 2)

1. A comprehensive literature search was conducted including domestic and foreign literature in order to determine the state-of-the-art related to head-up display concepts, symbology, hardware, and prior experiments and analysis.

2. Head-Up Displays now in service were reviewed both through on-site visits to HUD manufacturers and users (military and civilian) and/or visits by HUD manufacturers and users to NASA facilities.

3. Persons knowledgeable in HUD research studies, simulation, flight tests,, and operational use were surveyed with regard to such HUD factors as symbology/format, information content, mission-related effectiveness, etc. In addition, the findings of previous HUD surveys were reviewed and analyzed.

4. The primary conclusions of the review were as follows:

- o A HUD offers a means of reducing the operational workload of a pilot under both IFR and VFR conditions. This reduction in workload would apply to all flight deck personnel and could impact crew requirements for certain types of aircraft.
- o A HUD provides a means of achieving true redundancy in multipiloted aircraft regarding information for navigation, flightpath control, collision avoidance, alert and warning systems, and mandatory crew coordination (i.e., both pilots are simultaneously monitoring the instrument world, the real world, and prioritized alerting and annunciating systems).
- o Certain of the visual illusionary problems encountered in normal terminal area operations can be compensated for or eliminated through the use of a HUD, (i.e., whiteout, blackout, and erroneous vertical cues).
- o A HUD offers a technique by which the interdependence of crew coordinating and communications could be reduced during critical phases of flight without compromising flight safety.
- o HUD's have the potential for increasing cockpit flight instrumentation reliability by at least one order of magnitude using CRT technology when used in lieu of mechanical or electromechanical instruments. The reliability can be significantly increased even further by using LED's and EL technology instead of CRT's.
- o There are several production military HUD's which may be compatible for use in future air-carrier type aircraft. None of these HUD's which were produced for the military can be retrofitted into most of today's modern air carrier jet aircraft fleet without extensive modification.
- o There are several experimental HUD's which may be adaptable to the current fleet of air-carrier-type aircraft. At least one of these systems was designed with the constraints of being retofitable into existing air-taxi and air carrier type aircraft. However, none of these proposed HUD's has been evaluated to the extent necessary for such broad consideration or application.

- o A HUD system, with its related digital electronics, has proved to be cost effective in military application and has been predicted to be equally cost effective in civil application for future civil air-transport-type aircraft.

- o The advantages and limitation of a HUD when used as the primary flight display in commercial aircraft operations for all phases of flight have not been defined and documented. This applies both to the safety and economic aspects of a HUD system.

Based upon the findings of the report a determination is being made of the potential advantages of the head-up display concept. This is being done to insure that all advantages and disadvantages will be adequately evaluated in the research to follow. The information is also being used to analyze the type and amount of information pilots require for acceptable aircraft control during approach and landing. This will be related to current flight deck task analysis, taxonomies, display symbologies, and display techniques.

PART II. LABORATORY AND SIMULATOR TESTS TO SELECT CANDIDATE HUD

Each experimental research area to be addressed will include the following steps: (1) Establish the research objectives (based upon the findings of Part I), (2) Design the experiments with the primary emphasis upon HUD safety-related functions, outline the relevant test parameters, performance measurement techniques, analysis requirements, and data base, (3) Establish the requirements for the testing environment (simulator, laboratory, other), (4) Define the number, type, and qualifications of test subjects, (5) Develop appropriate means of assessing the test participants' prior attitudes and opinions regarding the HUD concept, (6) Prepare the test facilities (hardware, data collection/analysis systems, etc.).

Research Area 1. Title: "Preceptual Evaluations of Existing HUDs"

Objectives and Approach: To critically and systematically evaluate the most important human perceptual response capabilities using several existing operational HUD systems which have undergone optical evaluations. A question of major interest is what the HUD can contribute in the critical IFR to VFR transition phase of the approach in terms of providing necessary and sufficient vertical guidance information within a relatively short period of time. Some of the perceptual characteristics of the pilots which will be quantified include: capability of rapidly and accurately obtaining relevant flight information from different HUD symbologies versus standard cockpit instruments versus outside scene (simulated); time required, accuracy, and procedures involved in assessing available information which is of a discrepant nature (e.g., a conformal HUD display of a runway trapezoid which is out of registration with the runway seen out of the window); and the relative dependence of the pilot upon HUD-provided information versus out the window information in conditions in which the atmospheric visibility is intermittent.

The question "Can pilots become 'transfixed' or 'fascinated' by the collimated HUD image(s) and what is the resultant implication(s) for HUD symbology format/luminance/etc., design characteristics?" will be addressed.

Research Area 2. Title: "Symbology Evaluations of Existing HUDs"

Objectives and Approach: To critically and systematically determine the pilot's ability to detect, recognize, and use HUD information during the approach and landing phase of flight given various display symbologies. Initial studies will focus upon such display characteristics as scale factor, legibility, and layout format. Later studies will concentrate upon optimizing information transfer related to vertical guidance information in low visibility conditions. In support of the above experiments, it will be necessary to evaluate the perceptual fidelity of the outside scene generator's dynamics and related visual characteristics. It is planned that the current low visibility scene generators used on NASA/Ames' simulators will be empirically validated and upgraded if necessary so as to more nearly correspond with real-world visibility. In this way, the simulator evaluations of the candidate head-up display derived from other parts of this project, will be made more valid.

In order to select the candidate HUD for use in the full crew operational simulation evaluation program, it will be necessary to critically and comprehensively evaluate all prior experimental data obtained. These data will be compared to previously obtained data from other HUD programs (where possible) in order to help insure that all key display factors have been taken into account. This evaluation effort will provide data for selection of a candidate HUD that will be used in the full crew simulation to follow. It is hoped that the present state-of-the-art is such that an existing HUD may only require minor modifications, if any.

Research Area 3. Title: "Initial Piloted Simulation Tests of Selected Existing HUD Concepts"

Objectives and Approach: To make a preliminary assessment of several HUD symbology formats, to develop evaluation techniques, and to carry out preliminary tests of these techniques. A series of integrated, moving-base simulation studies will measure such parameters as glide path tracking accuracy, air speed control, opinion ratings of pilot users of the HUDs), etc. The possibility exists for monitoring pilot eye movement as well. These tests will be conducted in the Ames' Flight Simulator for Advanced

Aircraft (FSAA) using medium jet transport dynamics, collimated Redifon display, and computer-generated HUD. Of particular concern, will be the determination of what role HUD plays in providing necessary and sufficient vertical guidance cues in reduced visibility conditions.

Research Area 4. Title: "Optical Evaluations of Existing HUDs"

Primary Objective and Approach: To obtain quantitative and qualitative data on several existing operational HUD systems which will allow for a systematic, critical comparison between their optical characteristics and their perceptual, human factors, and other features to be determined in later experiments. These empirical tests will measure and evaluate such parameters as collimation accuracy, exit pupil dimensions (related to pilot head movement tolerances), combiner plate transmissions, etc. Since the basic optical characteristics of a HUD play a vital role in determining its eventual perceptual adequacy, it is essential to understand the relationship between these two factors before attempting to discover the (potential) causes of more subtle sources of difficulty in the information transfer process.

PART III. FULL CREW OPERATIONAL SIMULATION USING CANDIDATE HUD

This phase of the HUD evaluation project will be conducted by NASA with FAA assistance. Once the candidate HUD has been selected and made operational for simulator tests, it will be installed and checked out in an appropriate simulator facility. The final choice of the type of aircraft simulator to be used will primarily depend upon the research findings of the test planning phase outlined above in PART II and upon the availability of facilities.

Questions such as "How should a HUD be operationally integrated into the cockpit?", Will the use of a HUD increase stabilization of the flight path in non-precision approaches or reduce touchdown and/or glide path dispersions in low and/or intermittent visibility conditions?" will be addressed in this part of the project. The incorporation of the candidate HUD into the cockpit which also involves full crew coordination may also potentially identify further advantages of the HUD concept. Changes in current crew procedures resulting from the use of the HUD may also become apparent.

The following basic steps will be followed in the conduct of PART III: (1) Establish the research objectives (based upon the findings of PART I and II), (2) Design the evaluation experiments, (3) Obtain and install the necessary data collection/recording/management systems in the simulator, (4) Develop all required test procedures, pilot questionaire, and schedules, and (5) Select and train subject pilots for the simulation exercise(s). The full crew operational simulation evaluations of the candidate HUD will follow.

Since the many complex and interacting factors which are involved in the development of the candidate HUD will have been (primarily) determined during the end of PART II of this project, it is anticipated that only minor modifications in HUD symbology/format will be required during PART III. Consequently, it will be possible to concentrateupon these questions which are more related to operational issues, cockpit procedures, and overall engineering design factors. Close communication between the cognizant FAA program manager, experimenters, and potential HUD users will be maintained during this part of the project.

REVIEW AND ANALYSIS OF THE LABORATORY AND SIMULATOR DATA

An in-depth review of the data obtained from the entire project will be performed. In addition, a concurrent flight test program will be conducted at the National Aviation Facilities Experimental Center (NAFEC) in Atlantic City, by the FAA. Relevant data concerning the candidate HUD display found during this review phase will be directly applicable to the development of the test plan for flight tests. The NASA will assist the FAA in the flight test program planning.

SUMMARY AND FORECAST

As each experiment is completed, an interim report will be prepared by the cognizant NASA experimenter. Several reports are now under preparation and will be sent to FAA by September 1978. A final report on Part II will be completed by June 1979. Part III data collection will start in April 1979 with completion, including final report expected by the end of CY-1979.

A renewed interest in civil application of HUD recently appeared when several U.S. and International Airlines asked for HUD installations in their new generation aircraft. As a result, several airframe manufacturers have asked FAA for guidelines in the certification procedure for HUD.

To meet this requirement, FAA now has a more urgent need to obtain data and results from these NASA experiments. We have also recently initiated an FAA-sponsored HUD simulation program in conjunction with the wind shear program.

And finally, to verify the results of the simulation program, FAA is in the process of initiating a Request for Proposal for the procurement and system integration of a HUD system in an agency Boeing 727 flight test vehicle at NAFEC.

ACKNOWLEDGEMENT

Appreciation is expressed to Dr. R. F. Haines, NASA Ames HUD project coordinator for assistance in preparation of the description of the experimental design.

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HELICOPTER DEVELOPMENT PROGRAM

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BIOGRAPHY

Alvin F. Futrell received his Bachelor of Science degree in Engineering in 1946, from the United States Military Academy. In 1976, he received a Masters degree in Transportation from Goddard College at Plainfield, Vermont. He joined the Department of Transportation (DOT) in 1967, and has been in Systems Research and Development Service (SRDS) since 1974. Mr. Futrell has over 20 years of active flying experience in both rotary wing and conventional aircraft. This experience included a three year tour overseas as a helicopter unit commander, two years on the White House Staff, two assignments directing air taxi operations, and four years in a Federal Aviation Administration (FAA) Vertical/Short Takeoff and Landing (V/STOL) Office.

ABSTRACT

In March 1978, the FAA issued its initial Helicopter Program Plan. The Helicopter Development Program is intended to provide a coordinated research and development (R&D) effort directed by the Systems Research and Development Service to develop improved capabilities in the National Airspace System (NAS) for helocopter operations. The objective of the helicopter development program is to generate sufficient expertise and data relative to the unique capabilities of the aircraft to support FAA regulatory activities in developing and updating criteria, standards, and procedures directed at the safe and optimum operation of helicopters within the NAS. This paper presents the current status of the program.

BACKGROUND

With the first successful flight of the helicopter by Igor Sikorsky in 1939 and the first commercial helicopter certification of the Bell Model 47 in 1946, came the advent of an aircraft with the unique capability of hovering motionless over the ground and maneuvering in all directions free from the classic fear of stalling or from the need of a runway. Like all new concepts, however, much development was required to exploit its unique capability and commercial value. Payload, performance, and reliability were low, and maintenance and other operating costs were high. The helicopter's flight characteristics restricted it to the visual environment, and passenger acceptance was limited due to high vibration and noise characteristics.

All these factors militated against the helicopter's attractiveness as a commercial air vehicle except for those applications demanding the helicopter's versatility in vertical flight. Thus, the genesis of the commercial helicopter was somewhat bleak.

In the early 1940's, the military services adopted the helicopter where the practical value and potential was demonstrated. Development continued through the Korean War where the helicopter was used in significant numbers for medical evacuation. Fifty thousand wounded soldiers were evacuated in that war, dramatic proof of the helicopter's practicality. That vivid demonstration has been repeated, not only in Viet Nam, but also during countless civil emergencies all over the world.

Today, the characteristics of the helicopter have improved markedly over the early helicopters of the 1940's and the 1950's. During the past 20 years, payloads have increased fourfold, and the payload to gross weight ratio has gone from one-third to one-half. Maximum speeds have increased from 120 miles per hour (mph) to over 200 mph, with similar improvement in cruise speed. Maintenance man-hours per flight hour, a major consideration in the cost of commercial operation, have decreased from 25 to 3, and overhaul intervals have gone from 600 hours to 2,000 hours in many cases. The total cost of ownership and operation has decreased dramatically from 47 cents per seat mile to 14 cents. Control system and electronic technology developments have yielded a helicopter sufficiently stable to be flown in the instrument environment. Requests for IFR certification and operation are increasing. All of these trends attest to the enhanced viability of the helicopter.

Today, we have over 6,000 helicopters in the U. S. fleet. Of this number over 55% currently are engaged in commercial operation, about 30% in business/corporate activities and 15% in government-type work.

In the last few years, the helicopter fleet has been growing at an annual rate in excess of 12%. Thus, we can conservatively forecast that

by the mid-1980's, we will have around 10,000 helicopters in the fleet of which we expect about 5,000 will have IFR, virtually all weather capabilities. Helicopters are flying in support of oil drilling operations in the Gulf of Mexico, Alaska, and off the U. S. east coast, as well as in support of logging operations, executive transportation, traffic survey, and emergency medical and disaster relief. As the number and capability of helicopters increases, there is a commensurate need to generate data upon which to promulgate and update standards, regulations, and criteria pertaining to their certification and operation.

Major areas of research emphasis in the FAA program include: IFR capability; icing; improvement in environmental factors to include noise, crashworthiness, ride qualities; and finally, evolution of the Air Traffic Control (ATC) system and provision for greater operational capability in high density, offshore, and remote area operations. To carry out this activity, a helicopter program staff has been organized within the FAA Systems Research and Development Service to plan, coordinate, and manage the development activities in each of the functional areas needing improvement.

PRODUCTS:

CERTIFICATION

An initial report reviewing the airworthiness standards for certification of Helicopters for Instrument Flight regulation has just been completed by a contract with Pacer Systems, Incorporated. It specifically reviews the Interim Criteria, Federal Aviation Regulations, Advisory Circulars and other pertinent Federal Aviation Administration documents associated with the certification of Helicopters for Instrument Flight.

A review of current technology, existing data applicable to IFR helicopter operation and certification procedures has been accomplished. Identification of specific airworthiness requirements for helicopters operating in instrument meterological conditions is studied and special attention is given to aircrew manning configurations, pilot flight control workloads, helicopter trimmability, static stability, dynamic stability, handling qualities, analysis of time history data and documentation procedures, augmentation systems, autopilots and a review of certain flight test techniques.

An analysis was made of the numerous helicopters recently certified for IFR flight in order to establish the various systems utilized including avionics systems, display systems and autopilot type systems. Special emphasis was centered on the study of a most critical IFR Scenario depicted by marginal stability conditions due to aft c.g., and high clinb rates, etc., during missed approaches for CATEGORY I and CATEGORY II-ILS type procedures with IMC conditions of rain, night, turbulence, and crosswinds.

A follow-on corollary effort to recommend standardized certification procedures and to define required capabilities of pilots is in the final contract negotiation stages.

ICING

Response to a Request for Proposals (RFP) for a Helicopter Icing Technology Review has been received; the technical evaluation of proposals is underway and a contract should be let very soon. An inter-agency agreement with the U.S. Army is being prepared to extend the Army's icing flight test program by 2 months during the upcoming icing season.

The helicopter program staff coordinated with NASA personnel in organizing a conference on icing held at the NASA Lewis Research Center, July 19, 20, 21, 1978. Staff personnel attended this meeting to help resolve questions concerning the icing environment, the forecast of icing conditions, the effect of icing on helicopters and rules of operation under icing conditions.

ATC

Preparations have been made to define new ATC concepts for helicopters. These concepts will subsequently be evaluated by computer simulation, by flight simulation, and eventually by actual flight test. Figure I, is a plan view of a type of routing being considered. Figure 2, shows a typical copter approach in an offshore situation. Figure 3 is a type Gulf Coast year round off-shore profile.

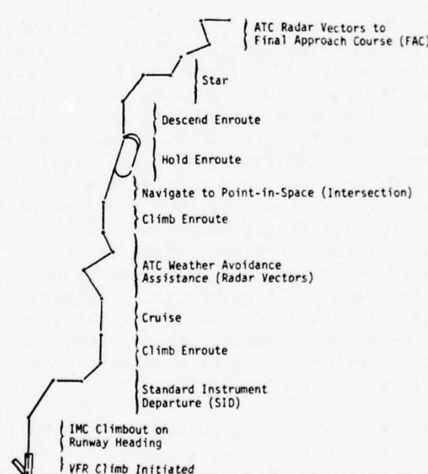

FIGURE 1 PLAN VIEW OF HIGH DENSITY IFR ENROUTE FLIGHT PROFILE

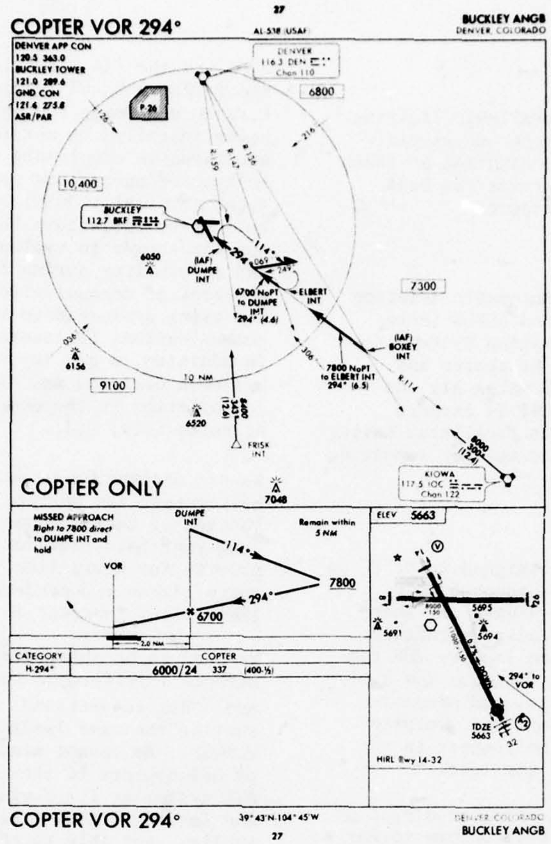

FIGURE 2 TYPICAL COPTER APPROACH

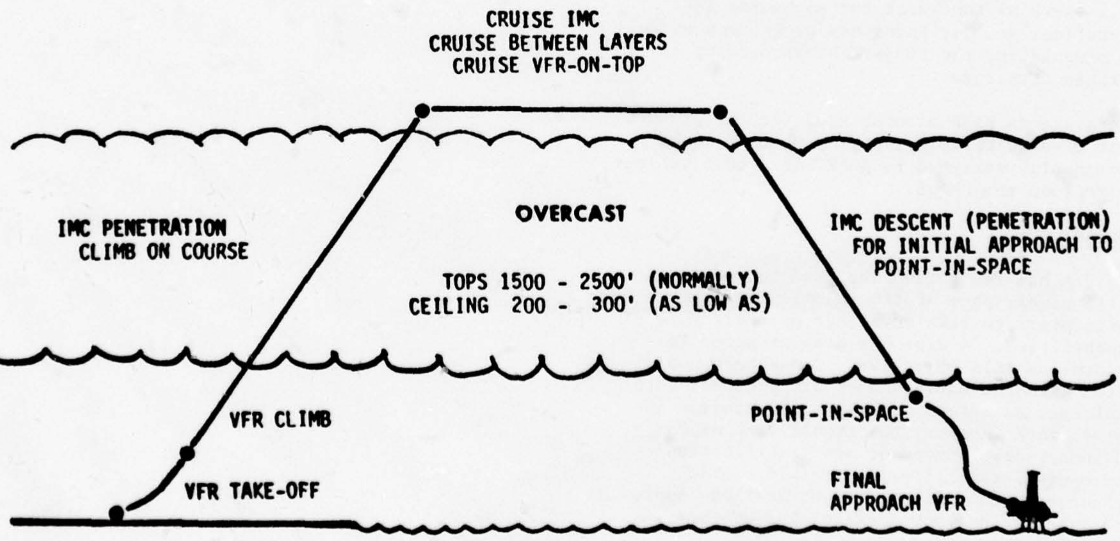

FIGURE 3. GULF COAST YEAR-ROUND OFFSHORE PROFILE.

HELIPORTS

A review is underway of all available lighting and marking devices for possible use on platform heliports. A thorough evaluation of these devices is being done to determine the best system for an all weather heliport.

WEATHER

The development of AV-AWOS (Automatic Aviation Weather Observation System) and ALWOS (Automatic Low-Cost Weather Observation System) for airports is being adapted to heliports and off-shore platforms. AV-AWOS makes all the required observations for a CAT II airport and ALWOS will be installed at facilities having an instrument approach, but no weather reporting system.

TEST VEHICLE

A CH-53 helicopter has been assigned to NAFEC as a test vehicle for the period through 1978. Flight tests have begun to evaluate off-shore communications and airborne radar approaches. Preparations have been made to improve VHF communications with helicopters flying at low altitudes off the New Jersey coast, and preparations have been made to install and evaluate Loran-C and Omega with this helicopter in the off-shore area and northeast corridor.

These tests are designed to establish a bank of data on the capabilities of helicopters to employ these systems for area navigation, approach and landing, and communications off-shore and in the northeast corridor. This information will serve as the basis for approving IFR operations and designing new procedures as well as pinpointing the subject areas needing further development.

Preparations have also started for the procurement of a suitable helicopter which will be permanently assigned to NAFEC as a test vehicle to replace the CH-53.

SUMMARY

The FAA has recognized the need to update the National Airspace System to make it possible for helicopters to take advantage of their unique capabilities. A plan has been prepared to accomplish this objective, it has been coordinated with the users and we are proceeding to implement an agreed program. The program involves work in every functional area of FAA's business; development of new certification and operational criteria, traffic control procedures, communications, navigation, approach and landing, heliport design, and weather reporting.

Initial activity has begun at NAFEC to improve the offshore helicopter operations at Atlantic City. A weather radar system has been installed in the CH-53A helicopter to obtain operational Airborne Radar Approach (ARA) criteria to assist RTCA and the FAA operational services in issuing specifications and landing minimas. Additionally, Loran-C and Omega/VLF navigational equipment are being installed to obtain navigation performance standards in compliance with AC 90-45A to support helicopter operations beyond the VOR/DME line-of-sight (typically JONM). Emphasis will be on helicopter operations below 1000 feet and at sunrise/sunset to evaluate signal propagation and reliability during these time periods. In the area of communications, new airborne antennas are being evaluated to improve VHF and HF communications far over-the-horizon operations. In addition, a new improved VHF sector antenna has been designed and has been approved for installation in the coastal regions adjacent to Atlantic City, N.J.

We are attempting to develop the NAS so that helicopters can operate efficiently taking advantage of their unique capabilities. In the long-run, this requires an airspace system to provide for navigation, communication and surveillance independent of line-of-sight limitations inherent in our present system.

We need to be able to operate helicopters without interference to, or from, airlines and other conventional aircraft, in many cases, sharing the same landing areas, but not the same runway. We cannot achieve the full potential of helicopters if they are to be handled in the ATC system as fixed-wing, conventional takeoff and landing - CTOL - aircraft. This principle applies, not only to enroute use of the airspace, but also to helipads on CTOL airports and to dedicated helicopters.

LORAN-C/OMEGA DEVELOPMENT PROGRAM

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BIOGRAPHY

George H. Quinn received his Bachelor of Science degree in Electrical Engineering in 1961 from the Pennsylvania State University. He joined the Systems Research and Development Service of the Federal Aviation Administration in November 1969 where he has been continuously involved in the development of long range navigation systems. From 1961 through November 1969, Mr. Quinn was employed at the FAA National Aviation Facilities Experimental Center (NAFEC) in Atlantic City as a project manager for the evaluation of long range navigation systems in aircraft.

ABSTRACT

This paper reviews the Loran-C and Omega navigation systems and their present status. Products of the FAA Loran-C and Omega development program and progress to the present are described. The specific technical approaches for several current projects are described in some detail.

LORAN-C AND OMEGA NAVIGATION

I. BACKGROUND.

A. LORAN-C.[1] Loran-C is a pulsed, hyperbolic system, operating in the 90-110 kHz frequency band. The system is based upon measurement of the difference in time of arrival of pulses of RF energy radiated by a chain of synchronized transmitters which are separated by hundreds of miles. The usable coverage from a Loran-C chain is determined by rated power of the stations, atmospheric noise, geometric relationship of the stations, and the specific capabilities of the receiver. The effective ground wave range from individual stations is typically 600 to 1,400 NM over sea water and depends on station power and the capability of the receiver. Measurements are made of a zero crossing of a specified RF cycle within each pulse. Making this measurement early in the pulse assures that it is made before the arrival of the corresponding sky waves. Precise control over the pulse shape ensures that the proper comparison point can be identified by the receiver. To prevent sky waves from affecting measurements, the phase of the 100 kHz carrier of each pulse is changed in a predetermined pattern. The nominal coverage area is based upon the assumption that the receiver being used can acquire and track Loran-C signals when the signal to atmospheric noise ratio is at least 1:3.

The Loran-C propagation mode most frequently used for navigation is the ground wave. Sky wave navigation is feasible but with some loss in accuracy. Although it is designed for use, and normally operated in the hyperbolic mode, Loran-C can be used to obtain accurate fixes by determining the range to individual stations. This is accomplished by phase comparison of the station signals to a known time reference to determine propagation time, and therefore range from the stations. This is referred to as the range-range (rho-rho) mode. It can be used in situations where the user is within reception range of individual stations, but beyond the hyperbolic coverage area. This method of using Loran-C requires that the user have a very precise and stable time reference. The high cost of equipment of this type limits the use of this mode.

The inherent accuracy of the system makes it a suitable candidate for aviation applications. While the 100 kHz signal is affected to some extent by soil conductivity characteristics and terrain, it can be received in mountainous areas where VHF and UHF systems are unusable. However, some distortion of the hyperbolic grid has been noted. The long range nature of the Loran-C system makes it particularly desirable for application to remote areas where suitable sites for short range navigational systems may be limited. By 1980 Loran-C signal coverage will include the U. S. Coastal area and much of the 48 contiguous states, part of Alaska, and the Hawaii area. An area in central U. S. will not be covered.

B. OMEGA.[1] Omega is a VLF (10-14 kHz) navigation system comprising at present seven of eight planned transmitting stations situated throughout the world. They provide usable signals over about 90 percent of the earth. Existing stations are in Norway, Liberia, Hawaii, North Dakota, La Reunion, Argentina, and Japan. Continuously available near worldwide position coverage will be attained when the eighth permanent station in Australia becomes operational in 1980. Omega generally utilizes phase comparison of sky waves from pairs of stations to form hyperbolic lines-of-position. The stations transmit time shared signals on four frequencies: 10.2 kHz, 11-1.3 kHz, 13.6 kHz, and 11.050 kHz, and each station also transmits a unique frequency (Figure 1).

The purpose of the four time-shared frequencies is to permit some uncertainty in knowledge of the location of the Omega receiver when it is initialized. By calculating differences between transmitted frequencies through phase measurements, the artificial frequencies of 3.4 kHz, 1.133 kHz, and 0.283 kHz can be created in the receiver. With the artificially created frequencies and the transmitted signals a position uncertainty of $\pm$144 miles can be resolved by the receiver and the correct position determined. The unique frequency transmitted by each station is intended for use as an additional and unambiguous source of information for navigation. At present, operational avionic units do not yet make use of the new 11.050 kHz time share frequency or the unique frequencies.

OMEGA SIGNAL TRANSMISSION FORMAT

STATION \ SEGMENT	A	B	C	D	E	F	G	H	FULL FORMAT TRANSMISSION DATE
NORWAY (A)	10.2	13.6	11⅓	12.1 †	12.1 †	11.05	12.1 †	12.1 †	January 1978
LIBERIA (B)	12.0 †	10.2	13.6	11⅓	12.0 †	12.0 †	11.05	12.0 †	February 1978
HAWAII (C)	11.8 †	11.8 †	10.2	13.6	11⅓	11.8 †	11.8 †	11.05	June 1978
N. DAKOTA (D)	11.05	13.1 †	13.1 †	10.2	13.6	11⅓	13.1 †	13.1 †	January 1978
LA REUNION (E)	12.3 †	11.05	12.3 †	12.3 †	10.2	13.6	11⅓	12.3 †	January 1979
ARGENTINA (F)	12.9 †	12.9 †	11.05	12.9 †	12.9 †	10.2	13.6	11⅓	April 1978
AUSTRALIA (G)*	11⅓	13.0 †	13.0 †	11.05	13.0 †	13.0 †	10.2	13.6	1980
JAPAN (H)	13.6	11⅓	12.8 ††	12.8 ††	11.05 ††	12.8 ††	12.8 ††	10.2	December 1978
Duration	0.9	1.0	1.1	1.2	1.1	0.9	1.2	1.0	
Start time	0.0	1.1	2.3	3.6	5.0	6.3	7.4	8.8	10.0

TIME (seconds)

*Trinidad Temporarily Filling G slot

Full format is shown:

† Unique frequency at each station

†† Frequency clearance pending

FIGURE 1. OMEGA SIGNAL FORMAT

In the Omega system, ambiguous lines-of-position occur as there is no means to identify particular points of constant phase difference, which recur periodically throughout the coverage area. The area between lines of zero phase difference are termed lanes. Single frequency receivers use the 10.2 kHz signals whose lane width is about eight miles on the baseline between stations. Three-frequency receivers extend the lane width to 72 NM, but these are more expensive than single frequency receivers. Because of the lane ambiguity, receivers must be set to a known location. Once set to a location, the Omega receiver counts the number of lanes it crosses in the course of a flight. This lane count is subject to errors which may be introduced by an interruption of power to the receiver, changes in propagation conditions near local sunset and sunrise and other factors.

The inherent accuracy of the Omega system is limited by the propagation corrections that must be applied to the individual receiver readings. The corrections are calculated and applied automatically in computerized receivers. The system is designed to achieve a predicatable accuracy of 2 to 4 NM (2-drms). This depends on location, station pairs used, time of day, and validity of the propagation corrections. The design repeatable accuracy is 1 to 2 NM (2-drms).

Propagation corrections are based in part on theory and modified to fit monitor data taken over long periods for localized areas. An extensive monitoring program is being undertaken by the Coast Guard under the aegis of the Navy which is managing overall implementation of the system. The monitor network will be used to verify the propagation model used to predict the corrections and the system accuracy in the area of the network stations. A number of permanent monitors will be maintained to update the model on a long term basis. Preliminary test data obtained in the operational environment have indicated that performance will satisfy the existing requirements established for oceanic airspace. However, the operational significance of lane slips, solar flares, and polar cap absorption must be considered.

Federal Aviation Regulations require the use of an independent position system with Doppler systems in order to limit potential navigation errors on flight legs of 1,000 NM or greater. Omega is the primary replacement for Loran-A in civil aircraft equipped with Doppler Navigators. It is doubtful that Omega will be acceptable as the primary navigation aid in the domestic air traffic system because of the possible lack of usable signals in the North Central U. S. Omega avionics are presently available from a number of commercial sources. Several of these units have been approved for use as an update system with Doppler navigators in air carrier aircraft on oceanic routes. Approvals to use Omega as a sole means of navigation on oceanic routes have been granted to general aviation operators, but not yet to air carriers.

II. PRODUCTS.

A. LORAN-C. The goals of the Loran-C development program are to: (1) determine whether Loran-C can replace the VOR-DME system in the post-1995 period, and (2) assess the suitability of Loran-C as a supplement to VOR-DME in areas not served by that system. The major product of this program will be documented support for a 1982 FAA decision concerning the VOR-DME replacement system. Intermediate products will be developments, studies, and evaluation reports on: (1) Loran-C signal stability in relation to use as a non-precision approach aid, (2) provision of an adequate system status advisory capability, (3) a study of the impact of the use of Loran-C navigation in FAA services and operations, (4) a low cost receiver prototype development, (5) development of a correction system to stablize Loran-C signals in selected geographic areas, and (6) a study of the effects of Loran-C self-interference (i.e., cross-rate) on aviation applications.

B. OMEGA. The Omega development program is directed toward use of the system: (1) as an oceanic navigation aid, and (2) as a supplement to VOR-DME in remote areas. Intermediate products will be: (1) an assessment of Omega signal adequacy on oceanic route structures (2) development of LF/VLF aircraft noise reduction methods, (3) development of a low-cost Omega receiver for general aviation application, (4) development of an Omega/VLF system advisory capability (5) an assessment of the effect of the use of Omega in FAA services and operations, and (6) development of test equipment for use by the FAA prior to authorizing specific avionics in the ATC system.

Some products of the Loran-C and Omega programs will be useful to industry, and others only to the FAA. In general, products of interest to industry will begin to become available in the 1981-1982 period.

C. PROGRESS. The FAA has been continually involved in the development and evaluation of Loran-C and Omega for over 15 years. Past work has served to guide on-going and planned efforts. The development program has recently seen the completion of the following projects: (1) the evaluation of a feasibility model differential Omega system, (report due Sept. 1978) (2) the evaluation of a 3.4 kHz Omega receiver[10] (3) the evaluation of three separate Loran-C receivers aboard air carriers on oceanic routes,[2,3,4] (4) a study of navigation requirements and systems to meet those requirements[11], and (5) an Omega flight test program in the Alaska area[5]. Projects that have been initiated but not yet completed include: (1) evaluation of a VLF noise cancellation antenna system, (2) development of a Omega/VLF signal monitor to provide an advisory service,[6,7,8,9] (3) evaluation of a combined INS/VLF system (report due Sept. 1978), (4) a program to collect and analyze Omega signal stability and interference near selected airport approaches, and (5) flight evaluation of state-of-the-art Loran-C avionics.

As noted above, three different Loran-C receivers were evaluated by three airlines to determine acceptability as a replacement for Loran-A. The evaluations were conducted in the North Atlantic, the Caribbean, and the North Pacific areas. Conclusions were that Loran-C would be a satisfactory substitute for Loran-A where usable signals were available. Airlines have chosen not to use Loran-C as a Loran-A replacement.

Prior to beginning hardware development for the Omega/VLF signal Monitor System a study was carried out to define that system. Involved in the study was a theoretical evaluation of both VLF communication and Omega signals over the continental U.S., the North Atlantic, and Alaska. Also involved in the study was an analysis of possible navigation errors related to airways structure and navigation requirements. Following completion of the study, an agreement was entered into with the Naval Ocean Systems Center in Dan Diego to assemble an Omega/VLF Monitor System. In April 1978 the initial, Omega only, version of the Monitor was delivered to NAFEC for preliminary evaluation. The VLF monitoring capability will be added to the unit, and the complete Monitor system will be returned to NAFEC for final evaluation in March 1979.

The 3.4 kHz Omega receiver evaluation noted was with a specially modified Canadian-Marconi Model CMA-740 receiver that could navigate in either the 3.4 kHz mode or in the more conventional three frequency hyperbolic mode. The 3.4 kHz is an artificial frequency derived from the difference between the transmitted 10.2 kHz and 13.6 kHz signals. It was expected that the 3.4 kHz receiver would have some immunity to Omega signal phase anomalies and less likely to acquire position errors known as "lane slips". Results indicated somewhat better performance in the conventional three frequency mode than in the 3.4 kHz mode. The Omega flight test program mentioned was in Alaska with a prototype low cost receiver (i.e., $6,000). It was found to have a high pilot workload, but might be suitable for use by many civil aviation aircraft.

In another effort a study was made to validate the civil air navigation requirements for CONUS, offshore and Alaska. A requirements matrix (Figure 2) was developed to provide a common basis for defining the requirements across all of the geographic areas considered. The second basic objective of the study was to assess the capability of Loran-C, Omega, differential Omega, and VLF communication signals toward meeting the requirements. Loran-C was found to offer all-altitude coverage for all geographic areas given signal coverage from existing and proposed chains. The primary drawback is the large area and, hence, the number of aircraft affected by a single station outage. With suitable redundancy Loran-C might meet the civil air navigation system. Omega lacks adequate signal coverage over the continental U. S. Therefore, Omega is a candidate only in Alaska, and in offshore areas. The VLF communications system is not dedicated to navigation, therefore, reliability becomes an issue. Used in in conjunction with Omega signals, the VLF communications signals can provide adequate redundancy and usable geometry.

III. TECHNICAL APPROACH

A. LORAN-C. The primary goal of the Loran-C program is to determine whether it can replace the VOR-DME system in the post-1995 period. To make this determination questions concerning Loran-C reliability, coverage, position ambiguity and accuracy, stability, interference, accessibility, presentation to the pilot, and compatibility, with other systems must be fully answered. Not all of the answers

USER	FLIGHT PHASE	REGION	COVERAGE						ACCURACY (2D)	OPERATIONAL							CAPACITY	COMPATIBILITY	SIGNAL RELIABILITY
			CONUS		ALASKA		OFF-SHORE			FLEXIBILITY	POSITION PRESENTATION	COMMON INPUT FORMAT	PILOT WORKLOAD	FAILURE ALERTS	POSITION RESOLUTION AMBIGUITY	TIME TO RE-ACQUIRE			
			VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL	VERTICAL	HORIZONTAL											
IFR	ENROUTE	NON-MOUNTAINOUS	2000 AGL TO FL 600	TOTAL	2000 AGL TO FL 600	TOTAL	500 AGL TO 10,000 MSL	200 NMI OFF-SHORE	±4 NMI 95%	YES (5)	COURSE DEVIATION, NMI (6) ρ/θ LAT/LON	YES	(7)	MUST BE AVAILABLE	LESS THAN 0.5% OF THE TIME	1-2 MIN	UNLIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
IFR	ENROUTE	MOUNTAINOUS	2000 AGL TO FL 600	(1)	2000 AGL TO FL 600	TOTAL	NOT APPLICABLE	NOT APPLICABLE	±4 NMI 95%	YES	COURSE DEVIATION	YES	(7)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.5-1 MIN	UNLIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
IFR	TERMINAL	HIGH DENSITY	200 AGL TO 14,500 MSL	(2)	200 AGL TO 14,500 MSL	(2)	200 AGL TO 10,000 MSL	(2)	(4,9) ±2 NMI 95%	YES	COURSE DEVIATION	YES	(8)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.25-0.5 MIN	UNLIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
IFR	TERMINAL	LOW DENSITY	200 AGL TO 14,500 MSL	(2)	200 AGL TO 14,500 MSL	(2)	200 AGL TO 10,000 MSL	(2)	(9) ±4 NMI 95%	YES	COURSE DEVIATION	YES	(8)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.5-1 MIN	UNLIMITED	AS PER PREVAILING SPECS	FAIL-SOFT
IFR	NON-PRECISION APPROACH		250 AGL TO 14,500 MSL	(3)	250 AGL TO 14,500 MSL	(3)	250 AGL TO 10,000 MSL	(3)	±1.5 NMI	YES	COURSE DEVIATION	YES	(8)	MUST BE AVAILABLE	PRECLUDE VIA SYSTEM DESIGN	0.25 MIN	UNLIMITED	AS PER PREVAILING SPECS	FAIL-SOFT

(1) Equivalent to current and increasing with time to reflect projected traffic density increases.
(2) All terminal areas being servied currently and those projected to be serviced.
(3) All airports currently with non-precision approach procedures and those where such procedures are expected to be required.
(4) 3D - +2.0 NMI, 4D - ±.15 NMI
(5) Not a hard requirement, but does have significant cost impact.
(6) Enroute preplanned direct only.
(7) Less than or equal to single waypoint VORTAC-based RNAV system.
(8) Less than or equal to dual waypoint VORTAC-based RNAV system.
(9) ±2 NMI in terminal maneuvering area (within 15 NMI of airport) ±4 NMI beyond 15 NMI from the airport.

FIGURE 2. NAVIGATION REQUIREMENTS MATRIX

are equally difficult. The present program concentrates on the signal stability, reliability, interference, and accuracy questions. Signal stability measurements will be made with a specially equipped test van throughout the Eastern United States. Equipment in the van will include an Austron Model 5000 Loran-C receiver, a Hewlett-Packard spectrum analyzer, and recording equipment. Signals will be monitored at various locations to include the normal airport environment, urban areas, and mountainous area. Specifically, measurements will be made in Washington, D. C., Baltimore, Philadelphia, and New York City to determine the Loran-C signal situation amid the possible interference generated by large cities. The mountainous areas to be investigated are Rutland, Vermont; Blacksburg, Virginia; and Dunkirk, New York. Airport environment measurements will be made at NAFEC. Sites at which measurements will be made were selected by a separate study. In addition to long term ground measurements, a program for Loran-C flight evaluation will be carried out by the FAA over a broad geographic area. A more specific evaluation will be conducted in cooperation with the State of Vermont within that State.

Loran-C avionics to be used in the flight tests will be the Teledyne Models TDL-424 and TDL-711. The TDL-424 is the more sophisticated system and should show the better performance. To be added to the program will be the measurement of possible interfering signals from commercial power lines. Some power companies are using radio frequency carriers transmitted along their lines to regulate loads by remote control switching. Some of the frequency used for remote switching are in the 90 kHz to 110 kHz Loran-C band. Potential interference by other radiating sources near the Loran-C band (e.g., Navy Communications) and self-interference by undesired Loran-C signals may also be examined.

System reliability is of great significance especially to the general aviation operator using a low cost Loran-C receiver. It is possible that such a low cost receiver would operate only from signals from one Master Station and two specific secondary stations. The failure of any one of the three stations would eliminate his radio navigation

service. Additional capability in the airborne unit would somewhat alleviate the problem, but cost would increase. Accuracy measurements will be made during flight tests at the National Aviation Facilities Experimental Center in New Jersey, and during the planned flights in Vermont.

B. OMEGA. There is a need to increase knowledge of Omega signal availability and reliability over most of the major oceanic air routes. This knowledge is needed to support decisions regarding the increasing use of Omega, and also support development of an effective system advisory service. The planned program includes the following steps:

(1) Procure digital data tape cassette recorders.

(2) Secure participation in the program by air carriers with Omega receivers installed.

(3) Lend recorders and a supply of tape cassettes to each of the participating organizations for installation in their aircraft.

(4) Establish a data analysis and reporting capability at NAFEC for processing of the data on the tape cassettes.

(5) Operate the data bank and issue periodic reports (e.g., probably monthly and quarterly).

The reports will include data on anomalous propagation found, discontinuities in signal reception, unexpected shifts in signal phase, loss of lane count, signal-to-noise levels, and also correlated data from Omega ground monitors and solar activity records. The FAA will suggest analysis methods for each type of data, but the final analysis method and data presentation format will be determined, to the greatest extent possible, by all participants and the FAA in cooperation. This is part of the effort to develop an effective system advisory capability, along with the Omega/VLF Signal Monitor System described earlier.

IV. SUMMARY AND REFERENCES

A. SUMMARY. Loran-C transmitters are being installed to provide marine navigation along the U.S. coastal area. Signal coverage will extend inland over a large part of the 48 contiguous states. The Omega system is operational over much of the world with seven of the eight planned stations operating. The FAA is examining the utility of both Loran-C and Omega for certain aviation applications. Loran-C is being considered as a possible replacement for the VOR-DME system in the post-1995 period. The rapidly expanding use of Omega on oceanic routes has indicated a need for additional data. With both systems the approach to solutions involves studies, data collection, and equipment development.

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THE PERFORMANCE OF A SIMPLE MICROWAVE LANDING SYSTEM CONFIGURATION

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ABSTRACT

The International Civil Aviation Organization (ICAO) recently selected the Time Reference Scanning Beam (TRSB) Microwave Landing System (MLS) for standardization as the eventual replacement for the Instrument Landing System (ILS). The transition to the new MLS will very likely be an evolutionary process throughout the world based initially on system expansion rather than ILS replacement. A simple, low-cost and relatively small MLS configuration called the "Small Community" (SC) configuration that is particularly easy to install and maintain could play a significant role in the initial stages of MLS use. Data from engineering acceptance tests are presented for one SC configuration developed in the U.S. program. These data confirm the maturity of the TRSB system design with regard to the implementation of simple systems that are suitable for use even at difficult sites. In addition to performance data, a description of the overall TRSB system concept and signal format is presented and the range of typical system hardware configurations is identified.

INTRODUCTION

In April 1978, ICAO selected the TRSB MLS as the eventual international replacement for the ILS. This section restates the principal objectives established for the MLS in the United States, outlines the National program for development of the system and introduces the ICAO system selection and standardization process that has remained a focal point within the U.S. development effort. Following sections describe the overall TRSB system and its signal format, and define typical hardware configurations that among them are capable of meeting the full range of established operational requirements. Emphasis is placed specifically on a simple hardware configuration called the "Small Community" configuration because it is representative of the equipment that will likely play a significant role in the initial operational implementation of MLS.

Principal MLS Objectives

Fundamentally, MLS was intended to meet the full range of operational requirements from the simplest needs of general aviation to the full requirements imposed by curved approach paths for noise abatement, landings in all weather conditions, as well as the special requirements of military tactical and shipboard operations. The requirements of the various users were to be met with hardware configurations appropriate to the operational and economic environment of each user, and the airborne and ground-based (surface) elements of each configuration were to be fully interoperable with each other. Fundamental too was the objective of producing a new system having greater freedom from siting effects that have tended to limit the utilization of the ILS. Of all of these, the objective of providing for low-cost, simple versions of the new system for general aviation use has been one of the most important objectives in terms of initial introduction and use of MLS, since general aviation has been the user often faced with difficult siting conditions and limited resources which in combination have rendered ILS service unavailable. MLS has represented a clear opportunity in this area for system expansion as opposed to ILS replacement.

National Program

Subsequent to the 1967 - 1970 work by the Radio Technical Commission for Aeronautics (RTCA) Special Committee 117[1] which defined the system concept and operational requirements for MLS, the Government prepared a National Plan for the Development of the MLS[2]. Under this plan, system contractors were selected to study the concepts and requirements set forth by RTCA for the two techniques identified by Special Committee 117 as having the greatest potential; that is, the Doppler and Scanning Beam techniques. Initially, in Phase I of the planned effort, 6 contractor teams studied various approaches to implementing these techniques (4 studied the scanning beam technique, 2 the Doppler technique). In 1973, 4 teams continued into the Phase II feasibility hardware development effort (2 contractors having been selected for each technique). A major program milestone was achieved at the conclusion of this effort in early 1975 werein, after an exhaustive 4-month assessment effort involving both national and international MLS experts, the U.S. decided to adopt the TRSB system as its candidate for international standardization[3].

ICAO System Selection

At its 7th Air Navigation Conference in 1972[4], ICAO adopted a set of operation requirements for a "new non-visual system for approach and landing" (the MLS) similar to that established by the RTCA. Further, the conference defined a program whereby ICAO would monitor States' programs directed toward the development of the new system, assess the capabilities of these candidate systems, and eventually select one for standardization. In 1977, the All Weather Operations Panel (AWOP) completed Phase I of the ICAO program by recommending that the system proposed by both Australia and the United States be adopted for international standardization[5]. Phase II of the ICAO program was completed in 1978 with the formal selection of TRSB as the new MLS at ICAO's All Weather Operations Divisional Meeting convened especially for the purpose of making the system selection. Phase

III of the ICAO program, preparation of Standards and Recommended Practices for MLS, is underway within AWOP. This work may be completed in about 1 year.

SYSTEM DESCRIPTION

TRSB is an air derived system in which ground based equipments transmit position information signals to a receiver in the landing aircraft. The position information is provided as angle coordinates and a range coordinate. The angle information is derived by measuring the time difference between the successive passes of highly directive, narrow fan-shaped beams which inherently provide an accurate means for the time measurements. The range information is provided by the conventional Distance Measuring Equipment (DME) technique.

The TRSB signal format is time-multiplexed, that is, it provides information in sequence on a single carrier frequency for all the angle functions (azimuth, elevation, flare and missed approach azimuth). The format includes a time slot for 360° azimuth guidance. The angle guidance channel plan provides 200 C-Band channels spaced 300 KHz apart, in the 60 MHz band between 5031 MHz and 5091 MHz. The range (DME) channel plan also has been defined to provide 200 channels.

Narrow fan-shaped beams are generated by the ground equipment and electronically scanned to fill the coverage volume. In azimuth, the fan beam scans horizontally and has a vertical pattern that is shaped to control illumination of the airport surface. In elevation, the arrays are designed to minimize unwanted radiaion towards the airport surface thereby providing accurate guidance to very low angles. It is this ability to control the radiation patterns of the ground antennas that allows the use of simple airborne processing and still achieve high resistance to interference from signal reflections (multipath).

A ground-to-air data communications capability is provided throughout the angle guidance coverage volume by stationary sector coverage beams that are also designed to have a sharp lower-side cutoff. This communications capability is used to transmit the identity of each angle function and to relay information (auxiliary data) needed for all weather operations.

The airborne equipment receives the ground generated sector and scanning beam signals associated with each angle function and, in sequence, determines the identity of the angle function and detects the scanning beam angle information. It subjects the received signals to acquisition criteria before they are accepted and continues signal validation following acceptance.

The principal features of TRSB provide a system with accurate performance, high integrity and very straight-forward implementation. The system uses a single unmodulated transmitter channel for each function which results in high integrity and reliability.

The signal-in-space is highly stable by relying on digital techniques to generate the scanning beams, monitor the equipment, and process the guidance signals.

TRSB can be installed and commissioned conveniently because of the absence of field adjustments in the antennas and associated equipment. Repair is simplified by the replacement of modules which require no further calibration to maintain continued accurate guidance. The TRSB ground equipment is monitored by a combination of field and integral monitoring to assure system performance and integrity, and provide the necessary maintenance alerts.

System Fundamentals

This section describes the TRSB measurement technique and summarizes system operational capabilities as well as the functional characteristics established to achieve them. In addition, an overview of the signal format is given.

Angle Guidance. The TRSB signal format is based on scanning fan-shaped beams through the coverage volume in alternate directions (TO and FRO). The "TO" beam is scanned with uniform speed starting from one extremity of the coverage sector and moves to the other. The beam then scans back again to the starting point, thus producing the "FRO" scan as shown in Figure 1 for azimuth. In every scanning cycle, two pulses are received by the aircraft. The time interval between the TO and FRO pulses is proportional to the angular position of the aircraft with respect to the runway.

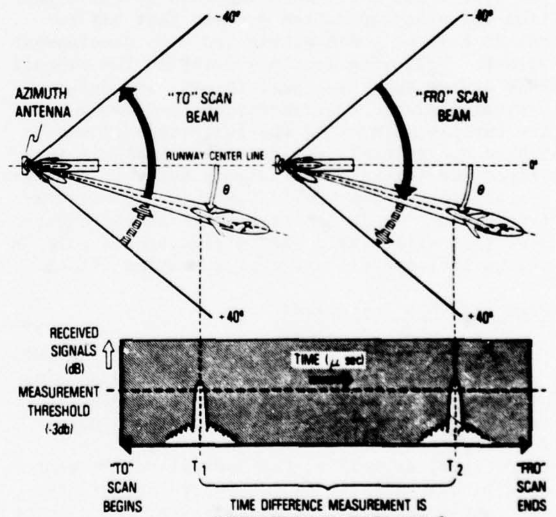


FIGURE 1. TIME DIFFERENCE MEASUREMENT.

All angle and data functions are time-multiplexed so that a single receiver-processor channel may process all data. Since the functions are inde-

pendent entities in the time-multiplexed function sequence, the receiver may decode them in any sequence. This is accomplished by providing each function with a preamble that, upon reception, sets the receiver for the function which follows. The function identification preamble is radiated as a stationary beam by a sector coverage antenna. The volumetric coverage of the scanning fan beam and the sector transmissions are illustrated in Figure 2.

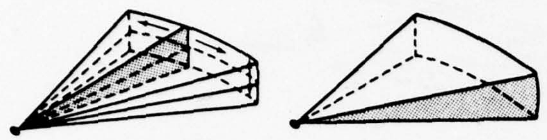


FIGURE 2. REPRESENTATION OF THE ANGLE AND PREAMBLE RADIATION CHARACTERISTICS.

All angular information is proportional throughout the coverage volume. Table 1 shows the regions of proportional coverage permitted by the TRSB signal format. All of these coverages exceed those stated in the ICAO Operational Requirement (OR). When regions of proportional coverage smaller than those stated in the ICAO OR are desired for the Approach Azimuth function, "fly-right, fly-left" clearance information can be provided over a wider sector to enhance intercept of the proportional region.* Reduced coverages from those shown in Table 1 for the elevation functions are implemented without "clearance" signals.

TABLE 1. TRSB COVERAGE CAPABILITIES

FUNCTION	PROPORTIONAL REGION
Approach Azimuth	±60°
Approach Elevation	0° to 30°
Flare	-1° to 15°
Missed-Approach Azimuth	±40°
Missed Approach Elevation[1]	0° to 30°
360° Azimuth[1]	360°

[1]Function not required by the ICAO OR.

Range Determination. Range information is obtained in the conventional manner by measuring the round trip time between the transmission of interrogation pulses from the aircraft and the reception of corresponding reply pulses from a ground transponder. The ground transponder is typically located near the stop end of the runway (i.e., collocated with the approach azimuth system). An L-Band DME that is compatible with existing equipment and provides improved accuracy and channelization capabilities is proposed for implementation. A range guidance function at C-Band has been developed and is included in the TRSB signal format. This feature can be deleted if it is determined that L-Band DME is adequate. Marker beacons may be used to indicate progress on an approach by users who do not require DME services.

*For instance, a proportional approach azimuth coverage of ±10° could be implemented for general aviation use with "left-right" clearance signals to ±40°, as in the U.S. Small Community configuration.

Flare Guidance. The signal format provides for a flare guidance element in accordance with the ICAO OR, which has been interpreted by AWOP as the need for precise guidance from 8 feet above the runway surface throughout the touchdown zone. Automatic landings have been made using the TRSB approach elevation signal and a radio altimeter, and this mode of operation is expected to be continued in the future. However, special or unusual circumstances can dictate the need for a separate ground-based flare capability. TRSB has demonstrated the performance necessary to meet the very demanding flare requirement stated in the ICAO OR using a combination of a narrow antenna beam, pattern shaping, and asymmetric signal processing.

Data Transmissions. The system has a very versatile data communications capability. Data are transmitted to all aircraft within the coverage volume (Figure 2) using Differential Phase Shift Keying (DPSK) modulation. These data transmission periods are time-multiplexed with the angle functions. Much growth potential is available in the data format.

Signal Format. Figure 3 illustrates a portion of the TRSB time-division-multiplexed (TDM) signal[6].

The features of the signal format are as follows:

a. The format provides the following guidance functions:
(1) Approach Azimuth
(2) Approach Elevation
(3) Range, using a compatible DME
(4) Missed Approach Azimuth
(5) Flare
(6) 360° Azimuth

b. The radio frequency allocation for angle guidance is at C-Band from 5031 MHz to 5091 MHz.

c. Signal polarization is vertical.

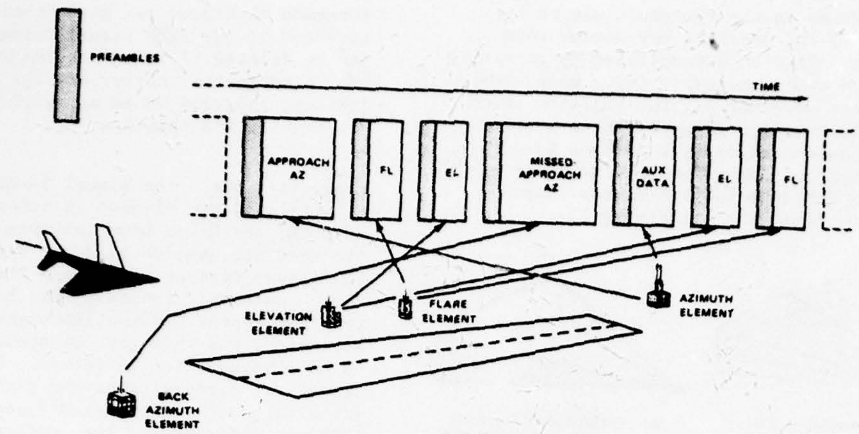
d. The proposed channel plan provides 200 channels for angle and range guidance.

e. The angle channels have a 300-KHz spacing.

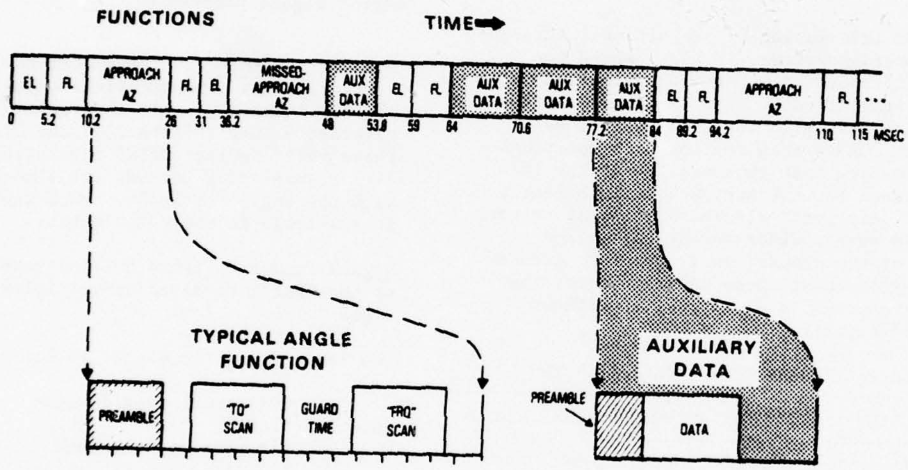
f. The minimum update (sampling) rates for the angle functions are shown in Table 2.

TABLE 2. ANGLE FUNCTION MINIMUM UPDATE RATES

FUNCTION	SAMPLES PER SECOND
Approach Azimuth	13.5
Approach Elevation	40.5
Flare	40.5
Missed-Approach Azimuth	6.75
Missed-Approach Elevation	6.75
360° Azimuth	6.75



(A) TIME SEQUENCING OF FUNCTION SIGNALS



(B) DETAILS OF TWO REPRESENTATIVE FUNCTIONS

FIGURE 3. TIME-DIVISION-MULTIPLEXED SIGNAL FORMAT

g. The coordinate system is conical for elevation and either conical or planar for azimuth.

h. Digital data are transmitted to provide site related data (e.g., minimum glide path angle, azimuth scale sensitivity), subsystem status, information to aid calculating decision height, and other information to facilitate Category III all-weather operations with high integrity.

i. A "clearance signal" (fly-left/fly-right) guidance capability with wide coverage is provided for those approach azimuth and missed approach azimuth elements designed to have narrow proportional coverage.

j. A ground-radiated angle test signal is transmitted which may be used for an end-to-end check in a receiver test mode.

k. An unmodulated signal is transmitted in the preamble which may be used by receivers for automatic selection of the strongest received signal if more than one aircraft antenna is used.

l. Special out-of-coverage indication (OCI) signals are transmitted by approach and missed-approach azimuth systems to ensure proper flag action when flying outside the system coverage volume.

CIVIL SYSTEM CONFIGURATIONS

The signal format allows a large variety of compatible system elements to be combined to form a given facility. The U.S. currently has identified three major configurations (combinations of elements) to satisfy the range of requirements.

These configurations are: (a) Basic, (b) Expanded, and (c) Small Community (see Fig. 4). The Small Community and Expanded configurations are functionally similar to the Reduced Capability and Full Capability configurations defined by AWOP for use in its system assessment. Additionally, TRSB can be realized in designs suitable for special applications, including man-transportable, shipboard, and other special purpose equipments.

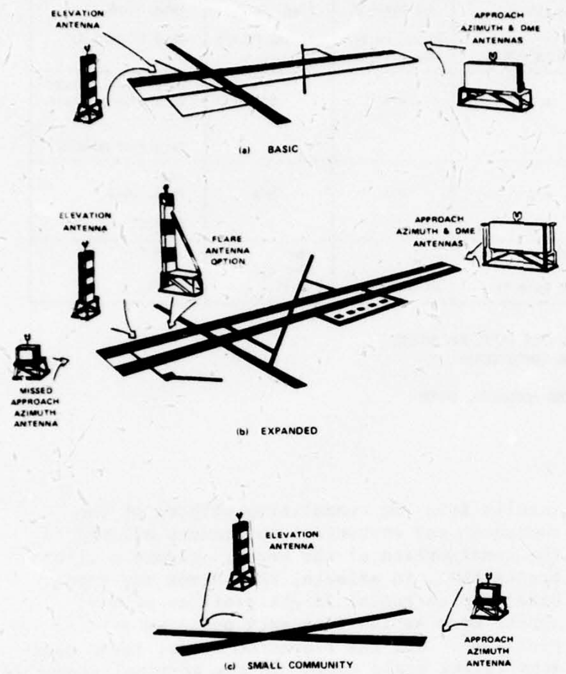


FIGURE 4. EXAMPLES OF TYPICAL GROUND CONFIGURATIONS.

a. The Basic configuration consists of the following functional subsystems:

(1) Approach azimuth, nominally located on the runway centerline beyond the stop end.

(2) Approach elevation, nominally located beside the runway near touchdown.

(3) DME transponder, nominally located with the azimuth equipment.

b. The Expanded configuration consists of all the basic subsystems plus the missed approach and flare subsystems. The Expanded configuration is designed with full redundancy to meet all the operational requirements of ICAO and all Category III requirements.

c. The Small Community configuration meets the need for a minimum service system and consists of:

(1) Approach azimuth
(2) Approach elevation
(3) DME or ICAO standard marker beacons.

This equipment is designed to meet Category I requirements in a cost-effective manner and does not have all the redundancy features needed for higher category all-weather operations.

A summary of the system performance capabilities of the various configurations is shown in Table 3 which includes representative military configurations as well.

TECHNICAL APPROACH

The principal objectives of the MLS hardware development program have been mentioned in the initial paragraphs of this paper. The objective of satisfying the operational requirements of the various users is achieved in the most economic manner by the several "tailored" configurations allowed by the flexible MLS signal format. A second objective, that of developing low-cost versions of MLS for General Aviation use, is promoted by ensuring that the MLS signal-in-space is very "clean" -- i.e., free of distortions due to error sources in the ground hardware (instrumentation errors) or due to signal reflections from the airport environment (multipath errors). The "clean" signal-in-space is highly desired as it leads to the lowest cost avionics -- receivers with simple signal acquisition logic and simple, straightforward processing of the received envelope for angle decoding.

Thus, if low-cost ground systems can be developed which have these "clean" signal characteristics, this second objective will be achieved to the highest degree possible. The remainder of this section is devoted to detailing the conditions under which a simple, low-cost MLS ground subsystem may achieve these signal characteristics; also, test data from one such system is presented and interpreted in terms of this objective.

Definition of System Errors

Error Components. The FAA specifications treat two components of the guidance errors. The "Path Following Error" (PFE) is the component which affects the aircraft position; this component is estimated by a low pass filter with a corner frequency of 0.5 radian/second for azimuth data and 1.0 radian/second for elevation data. The second component is "Control Motion Noise" (CMN) which affects aircraft attitude and control activity. The CMN is estimated by a pass-band filter with corner frequencies at 0.3 radian/second and 10 radians/second for azimuth data and at 0.5 radian/second and 10 radians/second for elevation data[7].

Examples of MLS flight test data are shown in Figure 5. The total guidance error is shown in the upper trace.* In the remaining traces, the total error has been resolved into PFE and CMN components.

Instrumental Errors. In the guidance region of most interest, near runway threshold, high signal-to-noise ratios (SNR) exist, and thus, signal-to-noise errors are not significant.

*The total error is also band-limited by a low pass filter in the MLS receiver which attenuates those frequencies above the range of interest for aircraft guidance or control activity.

TABLE 3. PERFORMANCE CAPABILITIES OF MLS CONFIGURATIONS.

CONFIGURATION / SUB-SYSTEM	COVERAGE/ACCURACY (2σ) SEE NOTE 3						
	EXPANDED	BASIC: WIDE APERTURE	BASIC: NARROW APERTURE	SMALL COMMUNITY	SHIPBOARD	JOINT TACTICAL	AIR TRANSPORTABLE CAT II/III
AZIMUTH	±40° Prop. Guid. PF:0.05° CM:0.04°	±40° Prop. Guid. PF:0.05° CM:0.04°	±40° Prop. Guid. PF:0.10° CM:0.08°	±10° Prop.Guid. ±40° Sector Guid. (See Note 1) PF:0.33° CM:0.10°	±40° Prop. Guid. PF:TBD CM:TBD	±40° Prop. Guid. PF:TBD CM:TBD	±40° Prop. Guid. PF:0.05° CM:0.04°
ELEVATION	0° to 20° Prop. Guid. PF:0.1° CM:0.05°	0° to 20° Prop. Guid. PF:0.1° CM:0.05°	0° to 10° Prop. Guid. PF:0.1° CM:0.05°	1° to 10° Prop. Guid. PF:0.16° CM:0.10°	-10° to 20° (See Note 2) PF:TBD CM:TBD (See Note 5)	1° to 20° Prop. Guid. PF:TBD CM:TBD	0° to 20° Prop. Guid. PF:0.1° CM:0.05°
FLARE	8 Ft above Runway to 8.5° Prop. Guid. PF:0.034° CM:0.02°	N/A	N/A	N/A	N/A	N/A	8 ft. above Runway to 8.5° Prop. Guid. PF:0.034° CM:0.02°
MISSED APPROACH AZIMUTH	±40° Prop. Guid. PF:0.1°	N/A	N/A	N/A	N/A	N/A	±40° Prop. Guid. PF:0.1°
DME	±40° 100 ft.	±40° 100 ft.	±40° 100 ft.	±40° (See Note 4)	±40° 20 ft.	±40° 360° Opt. 20 ft.	±40° 20 ft.

NOTES:
1. SECTOR GUIDANCE PROVIDES DIRECTIONAL GUIDANCE ONLY (FLY LEFT, FLY RIGHT)
2. LOOK DOWN ELEVATION GUIDANCE REQUIRED DUE TO SITING CONDITIONS: PROPORTIONAL GUIDANCE THROUGHOUT RANGE.
3. PF=PATH FOLLOWING ACCURACY, CM=CONTROL MOTION NOISE ACCURACY, (BOTH WITH REGARD TO MINIMUM GUIDANCE HEIGHT)
4. MARKER BEACONS OR TERMINAL AREA DME MAY BE USED.
5. TBD=TO BE DETERMINED

Therefore, the major instrumental error sources are the beam pointing errors which are a characteristic of the ground antenna. Simply stated, the scanning fan-beam of the MLS antenna may not point exactly in the direction commanded by the scan program. This error is variable (cyclic) throughout the scanned plane of the antenna and results from the cummulative effects of the component and mechanical tolerances allowed in the construction of the array. Figure 6 illustrates that, in azimuth, this error may appear bias-like on radial flight profiles or may appear more as low-frequency noise on orbital profiles[7]. For the elevation array, these characteristics would appear in the vertical (scanned) plane. Two aspects of the beam-pointing error are of particular importance: one - these errors can be made acceptably small in an antenna of reasonable cost; and, two - because of the digital techniques used to steer the MLS antennas, these errors typically do not vary significantly as a function of time. Thus, the antenna can be aligned so that this error source is

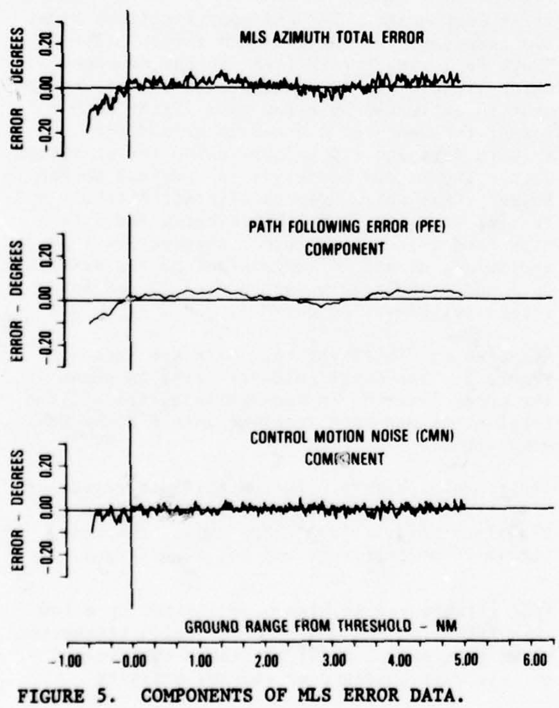


FIGURE 5. COMPONENTS OF MLS ERROR DATA.

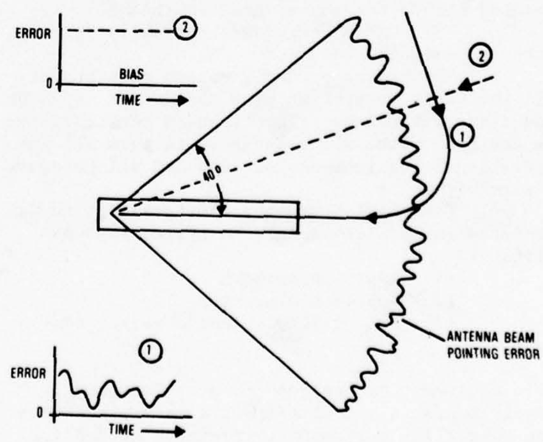


FIGURE 6. PATH FOLLOWING CONCEPT.

minimized in the centerline guidance region, and high quality stable guidance can be expected. The measured beam-pointing characteristic for the Small Community MLS azimuth antenna (to be discussed shortly) is shown in Figure 10. This characteristic is typical for microwave optics antenna designs such as the Rotman lens used in the Small Community MLS treated in this paper. Other generic antenna designs (such as the phased array) will have somewhat different characteristics. For all designs, the instrumental errors can be made "small" with reasonable effort and cost.

Multipath Errors. Significant errors can result if a strong reflected (multipath) signal should merge with the desired (direct) signal, and even the most exotic processors may not be able to resolve the direct from the multipath signal[8]. However, so long as the multipath signals have a minimum angular separation from the direct signal of about two beamwidths,* even very simple processors can acquire and maintain track on the direct signal without significant accuracy degradations. Outside this separation boundary the multipath is considered "out-of-beam" and within the boundary it is considered "in-beam". These conditions are illustrated in Figure 7.

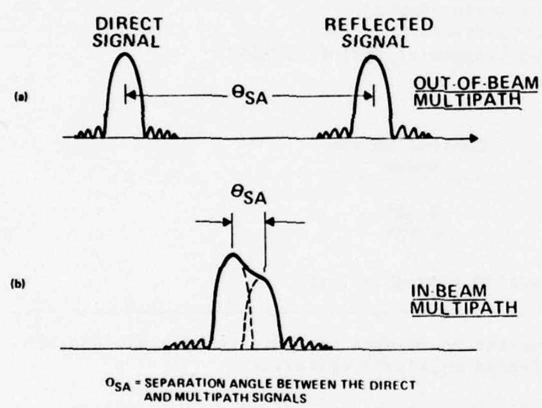


FIGURE 7. IN-BEAM AND OUT-OF-BEAM MULTIPATH.

By selecting ground subsystem beamwidths appropriately for the site concerned, the centerline approach region can be kept essentially clear of in-beam multipath signals; and shaping antenna patterns in the non-scan plane will keep the multipath signals at acceptably low levels throughout the remainder of the system coverage.

TEST RESULTS FOR A SMALL COMMUNITY MLS

Summary test results are presented in this section to illustrate the hardware realization of certain objectives of the MLS development program and to characterize the performance obtainable from a "minimum capability" MLS.

*The two beamwidth figure is conservative, as multipath errors are generally small until the separation decreases to less than 1.7 beamwidths.

Description of the System Tested

Table 4 lists the pertinent parameters of the Small Community system as detailed in FAA specifications[9]. The system is designed to provide useful coverages and accuracies consistent with Category I operations at smaller airfields (e.g., runway lengths of 5000 feet). While a minimum performance capability was intended, emphasis was placed on items of particular interest to the providing and operating agencies. Thus, maintenance monitoring and troubleshooting features are highly advanced, and the design includes the capability to interface with remote status and maintenance monitoring equipment at a distant, centralized facility using normal telephone lines. All electronics are included within the antenna case for both the azimuth and elevation subsystems. Figures 8 and 9 show the azimuth and elevation equipment.

Measurements of Instrumental Errors

As noted above, the instrumental errors of primary concern are the beam-pointing characteristics of the ground subsystem antennas. Examples of these characteristics for the azimuth and elevation arrays are shown in Figures 10 and 11. The data were taken on the antenna test range at the Bendix Communications Division as part of the factory tests conducted prior to system delivery in September 1976. Note that the azimuth characteristic has been optimized for the centerline region where the pointing errors are less than ±0.02°. Disregarding environmental effects then, the peak lateral displacement at the threshold of a 5000 foot runway would be expected to be less than 2 feet. Off centerline, the errors are allowed to increase somewhat which is consistent with operational requirements.

The elevation characteristic similarly has been optimized at the 2.5° glidepath which is consistent with FAA specifications. The pointing errors have a peak error of about 0.06° over the range of CTOL glidepaths. Again, without propagation effects, the peak vertical displacement at threshold could be expected to be less than 1.1 feet. This same magnitude of variation of the pointing characteristic is seen throughout the remainder of the elevation vertical coverage.

To summarize the effects of the beam pointing errors, note that the PFE specification for Category I performance on centerline is given in Table 4 as 0.33° for azimuth and 0.16° for elevation. The measured instrumental errors have used only a fraction of this budget implying that, if the antenna characteristics do not drift appreciably in the field environment and the multipath errors are well controlled, the system performance can be expected to be much better than the Category I specification.

Control of Multipath Errors[10]

The beamwidths chosen for this system are the maximum recommended in FAA specifications, which is consistent with the design goal that the MLS

TABLE 4. TRSB "SMALL COMMUNITY SYSTEM" DESCRIPTION
(Manufacturer: Bendix Corporation)

The Small Community system consists of Azimuth and Elevation guidance units. Each is self-contained with antennas and electronics in a single environmentally controlled case, including radome deicing.

Guidance is provided to 20 nautical miles with Azimuth fly-left/fly-right guidance within ±40° of runway centerline and proportional guidance within ±10° of runway centerline. Precision L-Band DME can be added to the Azimuth system, within the antenna case.

TECHNICAL SPECIFICATIONS

Frequency	C-Band, 5030-5090 MHz, 200 channels
Antennas	
Azimuth	3° beamwidth, using 4 ft. slotted waveguide radiators, microwave optics design (lens)
Elevation	2° beamwidth, linear dipole array, microwave optics design (lens)
Transmitter Power	20 watts
Range	20 nautical miles
Coverage	
Azimuth	±40°
	±10° proportional
Elevation	1° to 15° proportional
Reliability	1000 hours Mean Time Between Failure (MTBF)
Maintainability	0.36 hours Mean Time to Repair (MTTR)
Ground Power	120/240 volts, 20 kW
Monitors	Field Monitors
	Internal maintenance monitor (annuciator panel)
	Remote performance monitor (auto re-start)
	Available Remote Data Logging and Diagnostic System (RDLDS)
Performance	Category I
Specified Accuracies	(at 150' on 2.5° glideslope)

	Path Following Error	Control Motion Noise
Azimuth	0.33°	0.10°
Elevation	0.16°	0.10°

The subsystems may be used in either split-site or collocated configurations.

performance, particularly in the centerline region, should be essentially independent of the operating environment. As noted above, this goal can be achieved if significant reflections from the airport environment are angularly separated from the desired signal by more than two beamwidths. For objects in the azimuth plane of scan, airport obstruction criteria[11] require buildings of 50 foot height to be at least 850 feet from runway centerline. In angular terms, a large building near the threshold of a 5000 foot runway would be about 8° off centerline as seen from the azimuth site (see Figure 12). Thus, an approaching aircraft near runway centerline would receive the reflection separated more than two beamwidths (for the 3° azimuth antenna) from the direct signal, and no significant error would result from the multipath signal. Clearly, larger beamwidths reduce the zone around center-line which is free of multipath effects, and beamwidths greater than 4° would begin to generate "in-beam" multipath errors on centerline. Also, on longer runways, the 850 foot building offset would require smaller beamwidths in order to maintain the out-of-beam multipath criterion.

While the effects of lateral reflections in azimuth can be controlled by a suitable choice of beamwidth, the ground in front of the azimuth array can also be a strong reflector. Multipath from this source is controlled by shaping the lower side of the vertical pattern of the azimuth antenna. On this Small Community Azimuth, a 4-foot vertical aperture is provided for this purpose and results in about 8 dB/degree of pattern roll-off below the horizontal. The reduced ground reflection generates only small errors which are generally negligible. The vertical antenna pattern is shown in Figure 13. Analogous situations exist for the elevation array although in this case, the ground is the primary reflector in the (vertical) scan plane. Geometry considerations similar to the azimuth lateral hangar case show that glidepaths more than one beamwidth above the terrain* will be

*A glidepath one beamwidth above the terrain gives the required two beamwidths separation between direct and reflected signals.

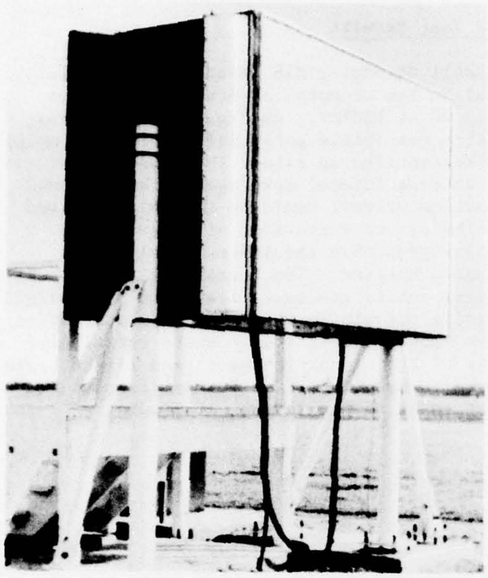


FIGURE 8. SMALL COMMUNITY AZIMUTH ANTENNA.

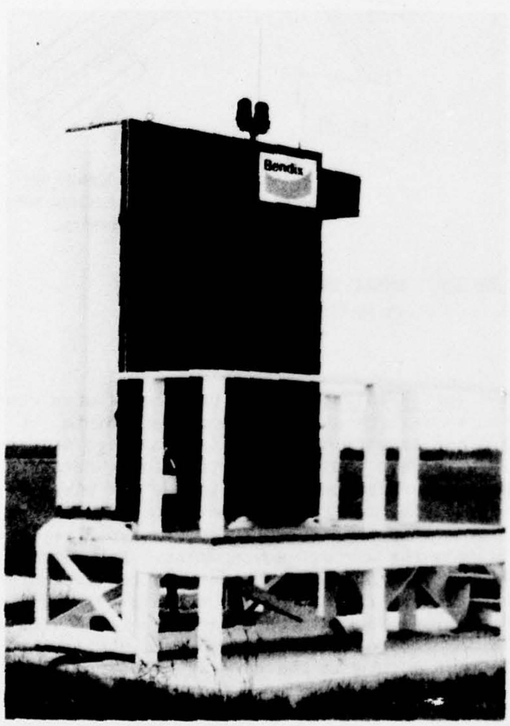


FIGURE 9. SMALL COMMUNITY ELEVATION ANTENNA.

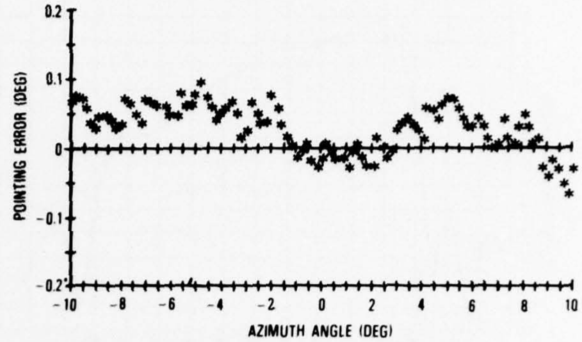


FIGURE 10. DYNAMIC RANGE TEST, AZIMUTH ANTENNA.

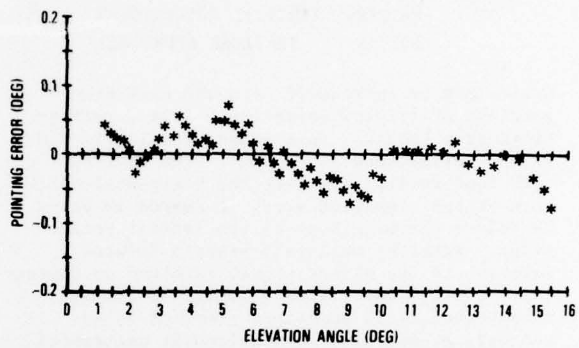


FIGURE 11. DYNAMIC RANGE TEST, ELEVATION ANTENNA.

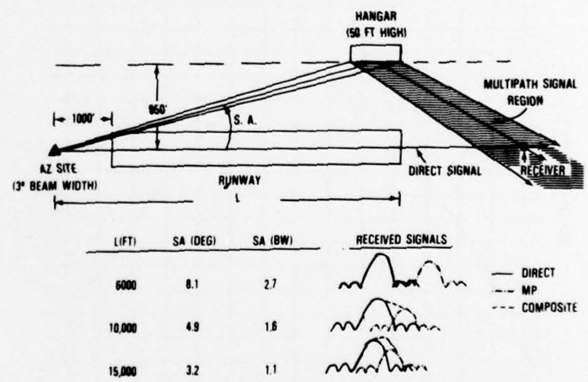


FIGURE 12. LATERAL REFLECTIONS IN AZIMUTH.

free of in-beam multipath errors from the primary (specular) ground reflection. However, the terrain in front of the elevation array may be rough enough to result in significant diffuse signal scattering which tends to raise the general noise level of the signal and may require an increase in separation angle to maintain a particular level of quality. Thus, the beamwidth criteria in elevation needs to be applied conservatively to assure high quality guidance at the lower glidepaths; very strong scattering from the ground could require as much as two beamwidths separation between the terrain and the lowest glidepath for high quality guidance.

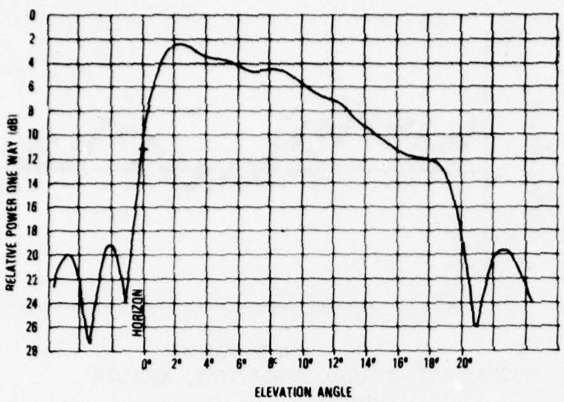


FIGURE 13. AZIMUTH ANGLE AND DPSK ANTENNA PATTERN, VERTICAL CUT (PATTERN 502, 4 FT. VERTICAL APERTURE)

Errors may be introduced into the elevation guidance by lateral reflections (e.g., reflections from hangars) in a manner similar to the ground reflections in azimuth. The control technique is also similar; the horizontal pattern of the elevation array is shaped in order to reduce the magnitude of the lateral reflections. With the multipath signals reduced relative to the direct signal received on centerline, quality centerline guidance is assured. This technique is sometimes referred to as centerline emphasis; the horizontal pattern of the elevation antenna is shown in Figure 14.

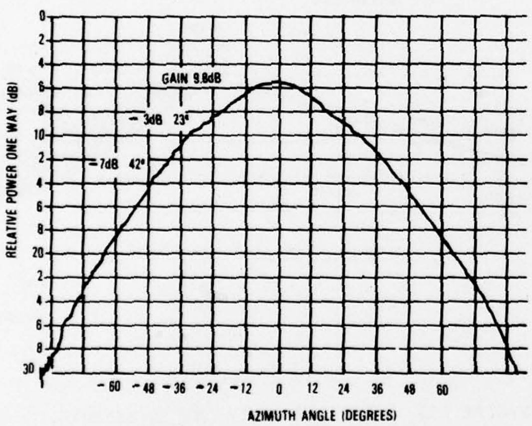


FIGURE 14. AZIMUTH PATTERN OF THE ELEVATION ANTENNA.

To summarize the techniques used to protect the MLS signal from environmental (multipath) effects, the antenna beamwidth selection is of fundamental importance to protect against in-beam multipath in the scan plane. In azimuth, the desired beamwidth is generally a function of the runway length; in elevation it is generally dependent on the lowest glidepath desired. Reflections in the plane orthogonal to the scan plane are controlled by shaping the vertical pattern for azimuth arrays and the horizontal pattern for elevation arrays. The degree of protection achieved is discussed in the following paragraphs which present the results of field testing of this MLS version.

Field Test Results

The Small Community MLS (Bendix) was initially installed for acceptance testing[12] to serve Runway 08 at NAFEC*. As Figure 15 indicates, the site has little potential for lateral multipath reflections in either the azimuth or elevation antenna lateral coverages. Thus, ground reflection effects would be the only expected contributors to distortion of the radiated signals other than the instrumental errors discussed earlier. The terrain in the vicinity of Runway 08 is generally flat with only slightly rising terrain in the final approach region of the runway. Both static tests (stationary probes of the signal-in-space) and flight tests were performed at NAFEC. Summary results are presented in the following paragraphs.

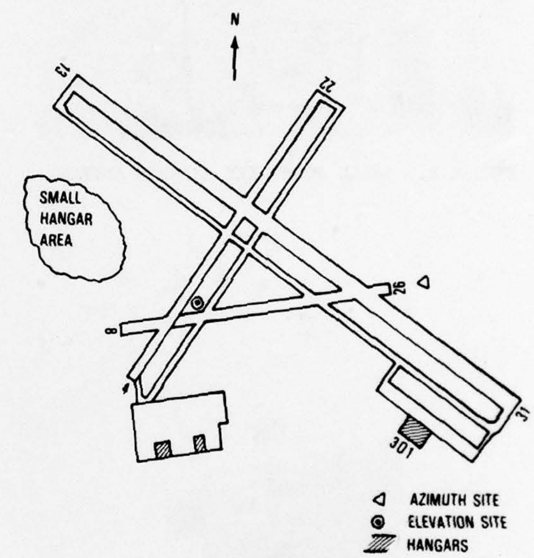


FIGURE 15. SMALL COMMUNITY MLS SITING AT NAFEC.

Static Test Results. Static pole tests were conducted at a large number of surveyed points within the azimuth and elevation coverage volumes. The bias errors indicated in the static data are of particular interest in that they are the average of the instrumental beam-pointing errors and any multipath errors caused by signal reflections from the airport environment. Figure 16 shows the beam-pointing characteristics (measured on the antenna test range and shown previously in Figure 10) of the azimuth antenna overlaid with the bias error data from a number of static field test points in the coverage sector. These

*NAFEC is the National Aviation Facilities Experimental Center located near Atlantic City, NJ, operated by the FAA.

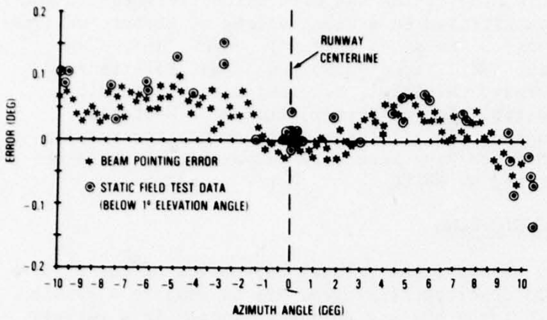


FIGURE 16. AZIMUTH POINTING ERRORS AND STATIC FIELD TEST BIAS ERRORS.

data show that, in general, the differences between the instrumental errors and the errors seen in the airport environment are very small -- i.e., the multipath effects (in this case mainly the ground reflections) are very well controlled by the directive antenna patterns. The one region around the -3° azimuth angle seems to show some environmental effects. We will discuss this region after the flight test data has been added to complete the picture at the higher elevation angles.

A similar treatment of the static test data for the elevation subsystem is presented in Figure 17. Static data are plotted for elevation

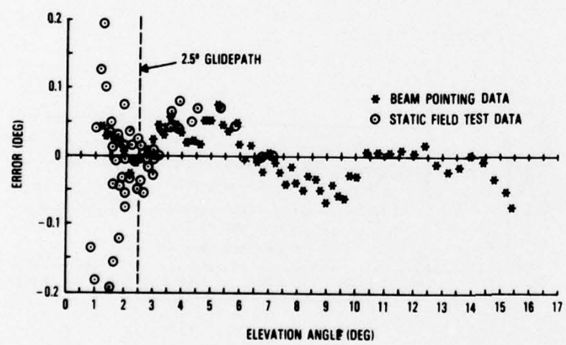


FIGURE 17. ELEVATION POINTING ERRORS AND STATIC FIELD TEST BIAS ERRORS.

angles from 1° to 7°. As expected, the data closely follow the beam-pointing characteristic until the elevation angle lowers to the 2° glidepath boundary for this 2° beamwidth antenna. Below this boundary, the multipath from the ground is "in-beam" and large and variable (due to the relative phases of direct and reflected signals) errors can occur. No effects other than these ground reflections are noticeable in the data.

<u>Flight Test Results</u>. This MLS version was flight tested extensively on Runway 08 at NAFEC where the precision instrumentation required to determine absolute error was available. In Figures 18 & 19, PFE samples of flight data are overlaid on the beam-pointing characteristics measured previously on the antenna range. As with the static data, the object is to assess the impact of the field environment on the system errors. Noteworthy is the very close agreement between the flight data and the basic antenna characteristics over the full range of azimuth and elevation angles. The only noticeable departure from the antenna characteristics was noted in the static data (see previous section) taken at low elevation angles around the -3° azimuth radial. Subsequently, this effect has been identified as a diffraction signal from the field monitor horn which was initially sited at a +0.5° elevation angle. Although the errors were well within the 0.33° PFE specification, the monitor subsequently was modified to assure quality guidance on and near the centerline region.

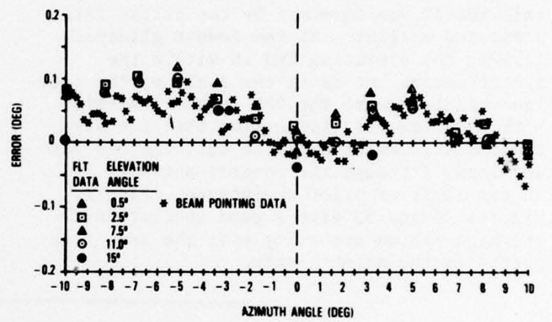


FIGURE 18. AZIMUTH POINTING ERRORS AND FLIGHT DATA PFE SAMPLES.

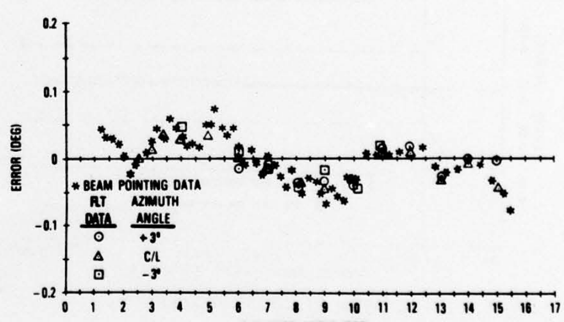


FIGURE 19. ELEVATION POINTING ERRORS AND FLIGHT DATA PFE SAMPLES.

The elevation flight data overlay also shows very close agreement between the samples of PFE data and the antenna pointing error characteristics, which gives very high confidence that the multipath sources are well controlled.

To complete the performance picture, flight data traces are presented in Figures 20 to 33 which interpret the total errors in terms of the PFE and CMN components. The accuracy requirements for the Small Community MLS and the accuracy

requirements for autoland operations are indicated on these figures.

The azimuth data shows no significant change in either PFE or CMN throughout the range of glidepaths presented (2.5° to 7°). This result is entirely consistent with the static data shown earlier and results from the azimuth antenna vertical pattern shaping which makes the azimuth signal highly resistant to ground reflection effects. Also Figures 24 and 32 can be compared as measurements of the system stability. The two flights were flown nearly six months apart, and there is essentially no change in the system characteristics.

A very similar result will be seen for the elevation data, except that, as the glide path angle decreases, the noise components of the error data increase due to the expected influence of the ground reflection. Again, this result was forecast by the static data presented earlier. At the lowest glidepath (2.5°), the elevation CMN is within the specification but is at the limit of the autoland requirements; the PFE is still within both requirements, indicating that the aircraft displacement would be satisfactory for autoland, although the control activity is at the limit of pilot acceptance. Finally, Figures 26 and 33 give a good indication of the high system stability over the same time period as the azimuth data.

This MLS version has been extensively tested and demonstrated in a wide variety of airport environments. The sites include: NAFEC, N.J.; Cape May, N.J.; Tegucigalpa, Honduras; Kristiansand, Norway; Charleroi, Belgium; Dakar, Senegal; Nairobi, Kenya; Shiraz, Iran; and Montreal, Canada. In all these environments the results obtained have been very comparable to those obtained at NAFEC.

CONCLUSIONS

In essence, the primary objectives of the U. S. MLS development program are to realize a system providing quality guidance signals in a variety of modular configurations which should be relatively easy to install, free of site-induced effects, highly stable, and readily monitored. These are the system characteristics which minimize overall system costs--especially in the avionics hardware.

Earlier work in the U. S. National Program[3] and the more recent assessment completed by ICAO[5] have demonstrated the embodiment of these desired characteristics in the "full capability" MLS implementations for use in complex hub-airport environments. Detailed engineering tests and extensive field demonstration experience now have shown these same desirable characteristics are achievable in a very simple "Small Community" MLS as well.

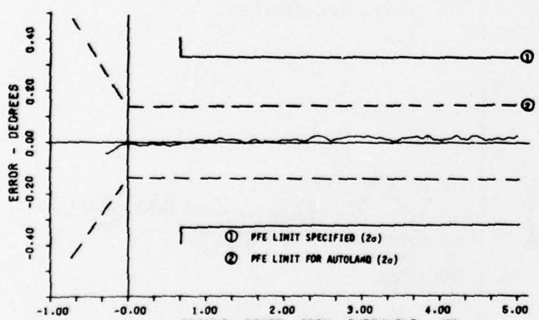


FIGURE 20. AZIMUTH PFE 2.5° GLIDEPATH

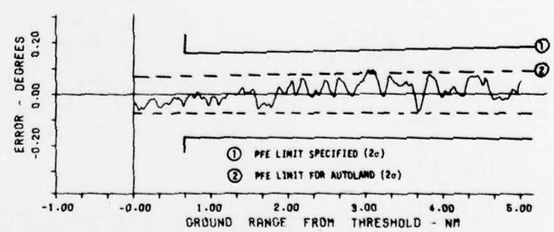


FIGURE 22. ELEVATION PFE 2.5° GLIDEPATH.

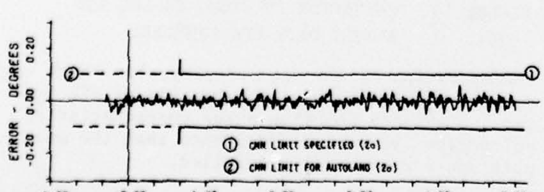


FIGURE 21. AZIMUTH CMN 2.5° GLIDEPATH.

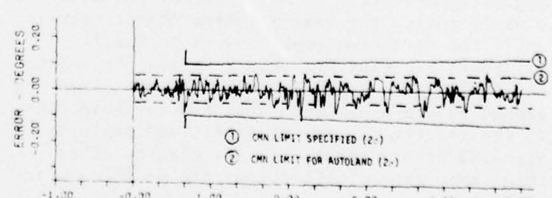


FIGURE 23. ELEVATION CMN 2.5° GLIDEPATH.

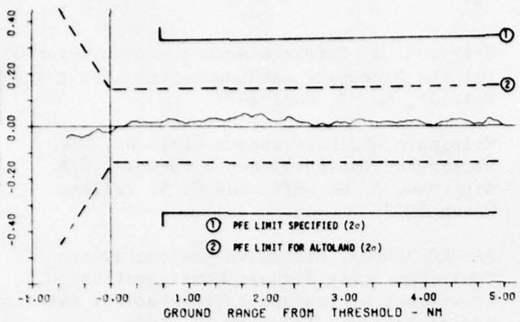


FIGURE 24. AZIMUTH PFE 3° GLIDEPATH (4/77).

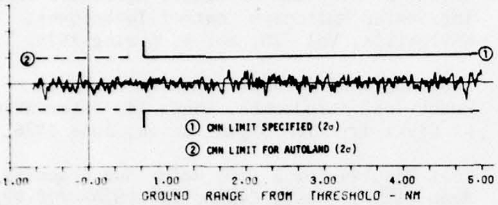


FIGURE 25. AZIMUTH CMN 3° GLIDEPATH (4/77).

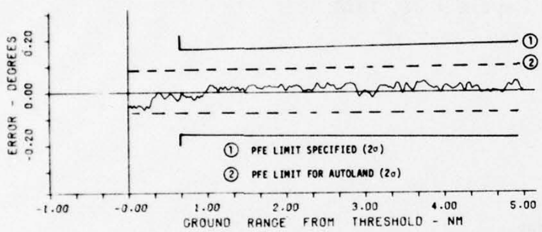


FIGURE 26. ELEVATION PFE 3° GLIDEPATH (4/77).

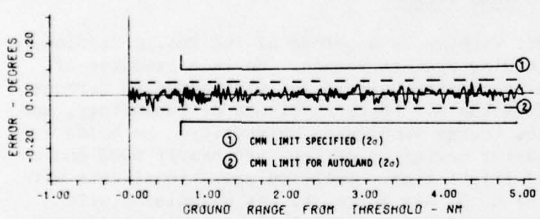


FIGURE 27. ELEVATION CMN 3° GLIDEPATH (4/77).

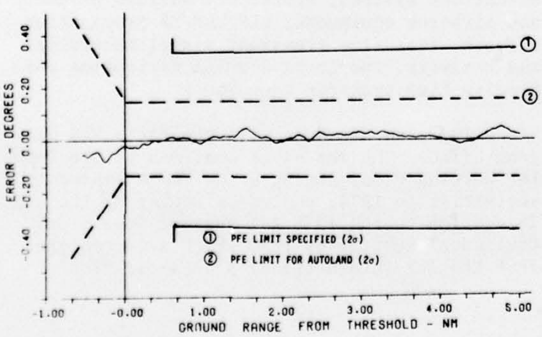


FIGURE 28. AZIMUTH PFE 7° GLIDEPATH.

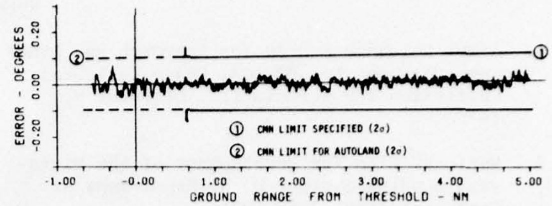


FIGURE 29. AZIMUTH CMN 7° GLIDEPATH.

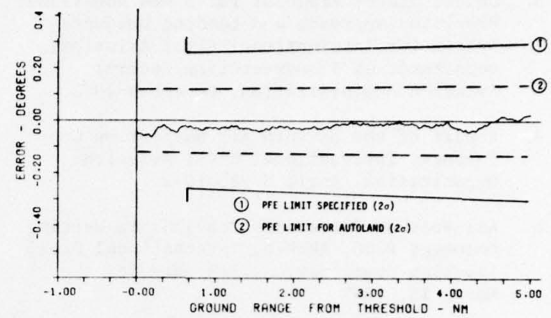


FIGURE 30. ELEVATION PFE 7° GLIDEPATH.

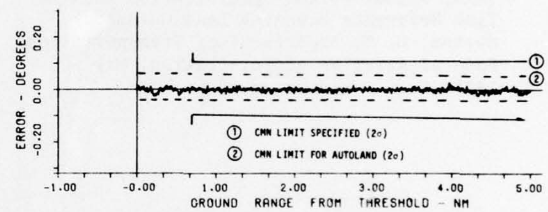


FIGURE 31. ELEVATION CMN 7° GLIDEPATH.

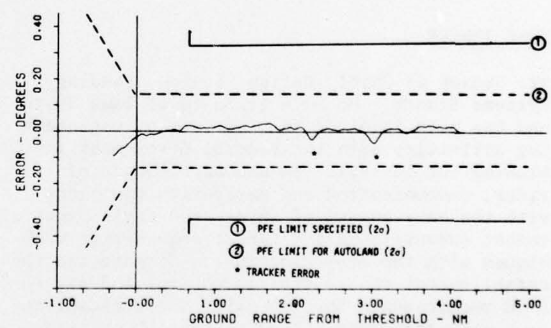


FIGURE 32. AZIMUTH PFE 3° GLIDEPATH (9/77).

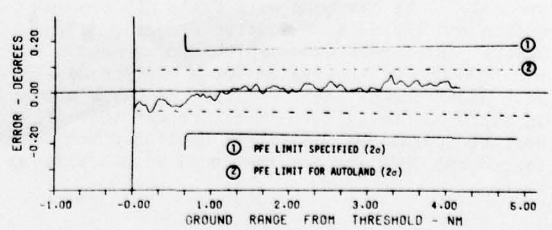


FIGURE 33. ELEVATION PFE 3° GLIDEPATH (9/77).

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BIOGRAPHIES

GENE JENSEN

Mr. Jensen is Chief, Design Section, Landing Systems Branch. He is a graduate of Iowa State and has been involved in a variety of engineering activities with the Federal Government including the installation and maintenance of radar, communication and navigation equipment with the Navy Bureau of Ships, the development of combat surveillance and target acquisition techniques with the Army Electronics Command and the establishment of air traffic control and navigation requirements for the Naval Shore Establishment with the Deputy Chief of Naval Operations (AIR).

Since 1971, he has been with FAA's MLS program office and served as Executive Director of the Central Assessment Group which recommended the TRSB MLS as the system for prototype development under the National Program and was a member of the U. S. Delegation to the recent ICAO All Weather Operations Divisional Meeting which selected the TRSB for international standardization.

DOUGLAS VICKERS

Mr. Vickers is a member of the Design Section, Landing Systems Branch. He is a graduate of Oregon State University, with advanced degrees from the Air Force Institute of Technology, and the George Washington University. He holds a master navigator rating with nearly 6000 hours of flight time. While on operational duty with the U. S. Air Force, he was associated with various developmental/implementation projects including air defence radar and ground/air communications systems, electronic warfare ground and airborne equipment, ELF/VLF/HF propagation effects, real-time transient signal recording and analysis, and Loran-C/OMEGA navigation and precise time transfer techniques.

Since 1972, he has been with the FAA's MLS program office. He served as chairman of the Doppler Working Group during U. S. MLS assessment activities in 1974, and was a member of the U.S. delegation to the 1978 All Weather Operations Divisional Meeting of ICAO which selected the TRSB MLS for international standardization.

FAA REMOTE TERMINAL SYSTEM FREQUENCY ASSIGNMENT MODEL

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BIOGRAPHY

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BIOGRAPHY

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ABSTRACT

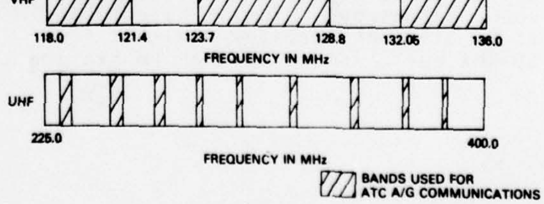
A system of interactive analysis was developed for the Federal Aviation Administration (FAA) to provide automated, quick-response capabilities for use by FAA in solving frequency management problems.

This paper describes the frequency assignment model that was developed as part of the FAA's interactive system. The model is used to make VHF (118-136 MHz) Air Traffic Control (ATC) frequency assignments, and the criteria used, and examples of the operation of the model, are discussed herein.

BACKGROUND

Direct voice communication between pilots and air traffic controllers is a vital link in the operation of the National Airspace System (NAS) by the FAA. To provide air traffic control communications, the FAA makes use of approximately 12.5 MHz of spectrum in the 118-136 MHz frequency (VHF) band to control civil aircraft, and approximately 40 MHz in the 225-400 MHz (UHF) band to control military aircraft (see Figure #1). With these frequency resources, the FAA must accommodate the need for approximately 3000 discrete communications channels. One channel usually consists of one VHF frequency and one UHF frequency, in order to provide control to both types of aircraft at once.

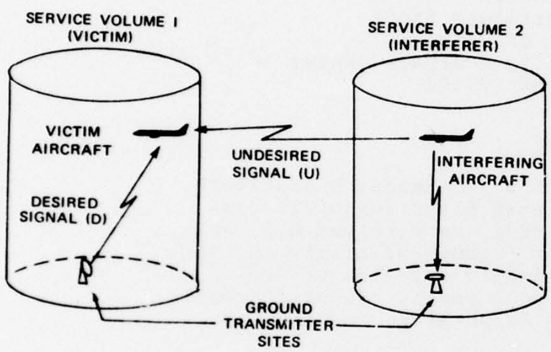
FIGURE #1
SPECTRUM USED FOR ATC A/G COMMUNICATIONS



Models are those specified in the FAA VHF/UHF Frequency Assignment Handbook.[1] This Handbook was derived from international standards and practices,[2] FAA research and development, and actual experience in frequency assignment. Some situations, such as 25/50 KHz interleaving, required that new criteria be developed. The intent of this section of the paper is to describe the most critical interference interaction analyzed by the VHF model, introduce the standard FAA criteria, and discuss those situations for which new criteria were required.

Of the potential cochannel interference interactions analyzed by the model, only the most critical interaction is discussed in this paper. This case is shown geographically in Figure 2.

FIGURE #2
INTERSITE INTERFERENCE INTERACTION

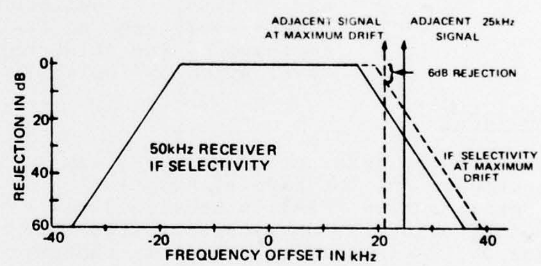


To provide adequate performance, the desired signal (D) at the victim aircraft in service volume 1 must be at least 14 dB greater than the undesired signal (U) from an interfering aircraft in service volume 2. The 14 dB D/U signal ratio must also be realized when the roles of the victim aircraft and interfering aircraft are reversed and for every combination of assignments served by the same frequency.

An assignment must perform as well in the presence of an adjacent channel signal as it does in the present of a cochannel signal. The IF selectivity of an airborne receiver designed for 50-KHz operation is assumed to provide at least 60 dB of attenuation to a signal offset by 50-KHz. An airborne receiver designed for 25-KHz operation is assumed to provide at least 60 dB of attenuation to a signal offset by 25 KHz. With this amount of rejection by the receiver of the interfering adjacent signal, a -46 dB (14 dB-60 dB) D/U signal ratio will achieve performance equivalent to the 14 dB D/U signal ratio specified for cochannel assignments. This would allow adjacent-channel assignments in adjoining service volumes. Even though the desired-to-undesired signal protection is achieved, the level of the undesired signal can exceed the muting threshold of the victim receiver if the aircraft in the adjacent-channel service volume is near the victim. This could cause an undesirable on and off action of the squelch and possibly desensitize the victim receiver. To avoid this, the FAA separates adjacent-channel volumes by 2 nautical miles (4 kilometers).

The same level of performance must also be achieved when an odd 25-KHz (e.g., 118.075) channel is interleaved between 50-KHz channels (e.g., 118.050-118.100). The IF selectivity of a 50-KHz receiver will only provide 6 dB of rejection to a signal offset 25 KHz (see Figure 3).

FIGURE #3
REJECTION OF A 25KHz ADJACENT CHANNEL
BY THE IF SELECTIVITY OF A 50KHZ RECEIVER



This value was obtained assuming that both the victim receiver and interfering transmitter are at their maximum allowable frequency drifts; i.e., 0,003% for airborne equipment[3]. Thus, for the worst case situation, to provide the required 14 dB of interference protection, 8 dB (14 dB-6 dB) must be obtained as a result of geographic separation.

The need for a communication channel is defined as a requirement, and the fulfillment of that need with a frequency is an assignment. The demand for ATC channels is increasing as air traffic continues to grow. The result is that a shortage of interference-free air/ground assignments exists particularly in areas of high traffic density such as New York, Chicago, Los Angeles, and Atlanta.

The FAA has in the past assigned channels at 50-KHz tuning intervals in the VHF band; i.e., 118.050, 118.100, etc. To help satisfy the demand for ATC channels, the FAA has implemented a change to 25-KHz channel spacing; i.e., 118.050, 118.075, 118.100, etc. Because of the high capital investment by the civil aviation community in airborne equipment designed to operate with 50-KHz channel spacing, assignments of the odd 25-KHz channels have been made very selectively. This situation has created a mixed (interleaved) environment of 25-KHz and 50-KHz equipment. The combined effects of limited spectrum, the mixture of 25-KHz and 50-KHz equipment in the environment, the need to consider interference interactions caused by collocating many facilities, and the presence of FM and TV transmissions in adjacent bands have made the manual assignment of ATC frequencies more difficult and time-consuming than in the past.

PRODUCTS/EXPECTED RESULTS

Difficulty in accommodating new requirements using methods current at the time, was first noticed around 1970. An extensive manual study performed by the FAA and computer-assisted studies performed by the Electromagnetic Compatibility Analysis Center (ECAC), indicated that, without major changes in the way the ATC bands were utilized, the FAA would be unable to satisfy all of the anticipated future requirements. Changes considered included a redeployment of all existing assignments and channel splitting. Based on these studies, the FAA also determined that automated frequency assignment methods would be required to derived maximum benefit from any large-scale changes in the use of the VHF/UHF bands. In 1971, ECAC was contracted to develop an assignment model for the FAA that would incorporate the established FAA assignment criteria, include cosite interference calculations as well as high-power TV and FM considerations, and handle the mixed 25/50-KHz equipment environment.

As the development of this model progressed, the need for a second model was identified. The initial, more comprehensive, model was employed to explore methods of improving spectrum use. The purpose of the second model was to make available to frequency managers automated frequency assignment methods to more efficiently utilize the spectrum when making case-by-case frequency assignments. The initial model was first used in 1973. At that time, frequency-redeployment and channel-splitting proposals were investigated using the model. Major redeployment of frequencies proved to be impractical; however, the change to 25-KHz channel spacing was endorsed. The model was then used extensively to plan the first phase of the change to 25-KHz channel spacing. A UHF version of this model has also been developed for planning future FAA use of the ATC portion of the UHF band.

The second model, identified as the operational VHF model, was ready for use in 1977. This VHF model resides at ECAC and is available for use by FAA frequency managers. The frequency manager provides the name, location, and service volume of the requirement. This information is entered into the model, which produces a list of candidate frequencies for the frequency manager. The development of a comparable UHF operational model is possible, but at present has been delayed because of questions concerning the classified data files required for comprehensive cosite analyses. The VHF assignment model will reside at ECAC for at least another year in order to refine and evaluate the performance of the system. The FAA will then decide if this system should be implemented in their Regional Offices, either via commercial computer timesharing or via a remotely located minicomputer, thus eliminating the present verbal interference with ECAC. This operational VHF assignment model is the subject of this paper.

TECHNICAL APPROACH

Assignment Criteria. The term criteria applies to the standard values of parameters such as desired-to-undesired (D/U) signal ratio, geographic separations, and frequency separations, used in the frequency assignment evaluation procedure. In most cases, the assignment criteria used by ECAC in the

To calculate the D/U signal ratios in the cochannel and 25/50-KHz interleaving cases, two assumptions are made. First, that the effective isotropic radiated power (EIRP) of the desired signal is equal to the EIRP of the undesired signals. Secondly, that the propagation of the signal can be approximated by free-space loss within line-of-sight and by infinite loss beyond the radio horizon. The power budget shown in TABLE 1 reflects typical ground and airborne system parameters and illustrates the first assumption.

TABLE 1

POWER BUDGET

Parameter	Desired Signal (Ground)		Undesired Signal (Aircraft)	
Transmitter Output Power	10 watts	40.0 dBm	25 watts	44.0 dBm
Line Loss		-1.5 dB		-3.0 dB
Antenna		+2.2 dBi		+0.0 dBi
EIRP		40.7 dBm		41.0 dBm

The D/U ratio is calculated as follows:

$$D/U = EIRP_1 - L_1 - EIRP_2 + L_2 \qquad (1)$$

where:

D/U = the desired-to-undesired signal ratio, in dB

$EIRP_1$ = EIRP of the desired signal, in dBm

$EIRP_2$ = EIRP of the undesired signal, in dBm

L_1 = the transmission loss from the desired ground facility to the victim aircraft, in dB

L_2 = the transmission loss from the interfering aircraft to the victim aircraft, in dB

Since $EIRP_1$ is approximately equal to $EIRP_2$, equation (1) reduces to:

$$D/U = L_2 - L_1 \qquad (2)$$

Since it is assumed that L_1 and L_2 can be approximated by free-space loss, equation (2) becomes:

$$D/U = 37.8 + 20LOG_{10}\, d_u + 20LOG_{10}\, f - 37.8 - 20LOG_{10}\, d_D - 20LOG_{10}\, f \qquad (3)$$

where:

d_u = the distance between the victim and interfering aircraft, in nmi

d_D = the distance from the desired ground facility to the victim aircraft, in nmi

f = the frequency, in MHz

Equation (3) reduces to:

$$D/U - 20LOG_{10}\ (d_D/d_D) \qquad (4)$$

Equation (4) is used in the assignment model to determine D/U signal ratios. For a 14 dB D/U ratio, d_U must be approximately five times greater than d_D. This method of calculating D/U signal ratios closely approximates results obtained using median propagation curves for most cases of interest.

One of the more difficult compatibility problems involves the collocation of equipment. To assist with the solution to this problem, adjacent-signal frequency separations and intermodulation and harmonic protection calculations have been incorporated in the models. The standard FAA adjacent-signal separation for collocated facilities is 500 KHz. An 0.2 nmi (0.4 km) radius for the site allows for variations in the reported and recorded geographic coordinates of facilities actually at the same location. The intermodulation products considered in this model are two- and three-signal, third-order combinations of FM and TV broadcasting signals in the 54-108 MHz band and/or other aeronautical facilities in the 108-136 MHz band. These products are considered by the FAA to be the most harmful sources of interference to ATC ground facilities. Because of their high EIRP's, broadcasting stations as far away as 15 nmi (28 km) from the site can produce harmful intermodulation and harmonic products. Since aeronautical stations operate at much lower levels, only those frequencies assigned to aeronautical stations located within 2 nmi (4 km) of the site are considered in the analyses. These distances were judged to be large enough to include in the analyses the most likely potential sources of interference in the area without overly restricting the number of possible assignments. The model will not assign frequencies that would result in adjacent-signal, intermodulation, or harmonic interactions. Frequencies that would produce harmonic

products in FAA UHF receivers in the area are also avoided. The 0.2, 2 and 15 nautical mile (0.4, 4 and 28 kilometer) criteria used for searching the data base were developed specifically for use in the assignment models.

Model Description. The objective was to develop a Remote Terminal Assignment Model that would utilize the FAA assignment criteria and perform the task in a timely manner. A responsive assignment model requires a data base that is structured to ensure fast access and efficient computational methods. Therefore, the model development was divided into two major tasks: 1) structure a data base and develop the necessary data management system to make the FAA-supplied data easily accessible to the model; and 2) develop an assignment capability that is consistent with the FAA-supplied criteria.

Data Base Design. Two types of data are required for FAA assignment model: data for the intersite analysis (requirement file), and data for the cosite analysis (background file).

The requirements file contains existing VHF assignments in the continental U.S., Canada, Mexico, and portions of the Caribbean. Each record contains the frequency, site name, site location, service-volume data (radius, altitude, service-volume center) and the unique requirement identification (ID) in the Government Master File (GMF). If the frequency serves an en route function (low-altitude or high-altitude), the latitude and longitude points that describe its multipoint service volume are also included in the record.

The second data file, the background file, contains those frequencies in the U.S. that are most likely to cause cosite problems for VHF assignments. Sources for this file are:

GMF: 108-136 MHz and 225-400 MHz bands

FCC: 54-108 MHz band

ARINC: 118-136 MHz band.

The background file is ordered by longitude, to permit rapid access to records for a specific geographic area. Each record in the background file contains the site latitude and longitude and the associated assigned frequency.

Assignment-Model Development. The assignment model must be able to perform data-base modifications and make the necessary cosite and intersite calculations. The initial assumption for any execution of the model is that all existing ATC requirements are currently satisfied. Any assignments to be made will result from new ATC requirements or requirements that need a frequency change. The model is divided into two sections: assignment problem definition, and assignment problem solution.

a. Assignment Problem Definition - The model provides the user with the ability to change the file to reflect the operating environment that will require new frequencies and/or frequency changes. Changes to the file are made by entering the unique GMF ID number, which enables the model to access the requirement that is to be modified or deleted. New requirements are entered by specifying the site name and location and all pertinent service volume information. The assignment process begins after all file changes have been entered.

b. Assignment Problem Solution - The process initiated by the user by specifying the cosite and intersite assignment criteria. The standard FAA criteria, discussed earlier, are preset in the model; however, the frequency manager has the flexibility to modify these criteria to account for unusual circumstances. Next, the user determines the frequency resources by specifying the channel spacing and frequency range or designating specific frequencies. Finally, the user specifies the requirement to be satisfied.

After all input data are specified, the model proceeds to the cosite and intersite analyses. To initiate the cosite analysis, frequencies are selected from the background file within a specified radius of the site where the frequency is to be assigned. The standard radius values are used; i.e., the 0.2; 2; and 15 nmi radii mentioned earlier. The model prohibits assignments that might contribute to such cosite interference phenomona as adjacent-signal, intermodulation, and harmonic interactions.
The cosite analysis provides a list of all denied frequencies and the reason(s)

for their denial. The intersite analysis begins by sequentially considering those candidate frequencies that have met the cosite criteria. These cosite-acceptable frequencies are tested to determine if they meet the cochannel and adjacent-channel criteria. Frequencies that meet the intersite criteria are shown to the user. The user may select the displayed frequency for assignment or continue to search for alternate acceptable frequencies. When a frequency is selected by the user, the model is instructed to record the assignment on a temporary basis and the user then designates the next requirement to be assigned a frequency. All frequencies assigned in a given execution of the model meet the FAA criteria and are compatible with the environment and other selections made during that execution. The data base reverts to its original configuration upon completion of the problem.

Sometimes, no frequency exists that meets all of the specified criteria. In this case, the user can return to the problem definition portion of the model to "free-up" a frequency. Frequencies can sometimes be made available to satisfy the new requirement by shifting the frequencies associated with one or two existing assignments. The file can handle 10 changes for any execution; therefore, the number of frequency shifts is limited. Frequencies for existing assignments so affected must be reassigned. Presently, the candidates for shifting are usually restricted to high en route facilities that can be reassigned on 25-KHz channels. (Only the high en route requirements utilize 25-KHz channels at present.) All other requirements are satisfied with 50 KHz channels.

Typical Examples. The FAA frequency managers have been using this model for over one year. In that time, over 100 operational frequency selections have been made with the model. In making these selections, the model has performed well and the results have been favorably received by the FAA Regional Frequency Managers.

The two examples below are typical of assignment problems that were solved by the model. The first example illustrates a problem in which an existing assignment had to be changed and the second example illustrates how an assignment for a new ATC requirement is determined.

Example 1 - A low en route assignment at Dayton, Ohio, presently using 134.450 MHz, was interfering with a high en route assignment at Brunswick, Georgia. The calculated D/U signal ratio was 10.1 dB. There was also an intermodulation problem on 134.450 MHz. No violation free 50-KHz channels were available, so the frequency of an existng assignment had to be changed to accommodate Dayton. One of the best candidate frequencies for Dayton was 127.850 MHz, because only one existing assignment (Portsmouth, Ohio) would need to be changed to permit Dayton to use 127.850 MHz. The assignment at Portsmouth was a high en route frequency that could switched to a 25-KHz channel. Therefore, Portsmouth was changed to 135.175 MHz and Dayton was assigned on 127.850 MHz.

Example 2 - A local control frequency assignment at Boise, Idaho, was needed to serve general aviation aircraft, many of which have vintage radios that tune only to channels spaced at 100-KHz intervals in the 118.0-126.9 MHz band. Initially, only two signal third order intermodulation protection was specified and three frequencies, 120.6, 120.7 and 125.9 MHz, passed all the criteria. It was later learned that the three-signal intermodulation protection was required which resulted in only 120.6 MHz meeting the criteria. Therefore, 120.6 was proposed for assignment at Boise.

SUMMARY

A frequency assignment model has been designed to help the FAA frequency managers make assignments that meet all of their prescribed assignment criteria. The model provides the user with a variety of capabilities not generally found in a single model, and offers a substantial savings in time, effort, and regional resources. Cosite calculations for any site in an urban area would normally take an engineer many hours to complete. The model performs the cosite analysis, including a search for the frequencies to be considered, in a matter of seconds. The model also gives the frequency managers the flexibility to define each assignment problem to reflect conditions of which only they might be aware, and this knowledge is often a very important ingredient in a go/no-go assignment situation.

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